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Regression Simulation of Turbine Engine Performance

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March 1979

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The results of developing six alternate calculation procedures for parametric turbine engine performance computer programs is presented. The alternate procedures were evaluated separately and then collectively in a baseline parametric engine performance program. The alternate procedures dealt with thermodynamic properties, matrix coefficient prediction, regression of component characteristics, afterburner calculations and regression of the compression process. Analysis of the combined procedures resulted in a cost reduction of approximately 46 percent with average deviations in engine net thrust and fuel flow rate of less than 0.7 percent.

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FOREWORD

This report describes the study effort conducted by the Detroit Diesel Allison, Division of General Motors Corporation, and sponsored by the Air Force Aero Propulsion Laboratory, Air Force Systems Command, Wright-Patterson AFB, Ohio under Contract F33615-77-C-2071, AF Project No. 3066 with James R. Ruble, AFAPL/TBA, as Project Engineer.

The work reported herein was performed during the report period of September 1977 through February 1979. Richard A. Sulkoske was the Detroit Diesel Allison Program Manager and the technical work was performed by Robert E. Clark, Development Engineer.

This report covers all work done under the Task I contract of the Regression Simulation of Turbine Engine Performance Program. When referring to this program in the text which follows, the abbreviation RSTEP is used.

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ABBREVIATIONS AND ACRONYMS

APL — Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Dayton, Ohio

Cp — Specific heat at constant pressure

eff — Efficiency

FN — Engine net thrust

h-lambda — Gas enthalpy adjustment used in burner temperature rise calculations

psi (ψ) — Term used in turbine design - ψ^* being design value

$$\psi^* = g\ J(\Delta H^*)/U^2 = 32.174 \times 778.156 \times \Delta H^*/U^2$$

where: ΔH^* = turbine design point enthalpy change
U = turbine blade mean-line velocity

$$\text{then: } \psi = \frac{\Delta H}{\Delta H^*} \times \left(\frac{\%\ N/\sqrt{\theta^*}}{\%\ N/\sqrt{\theta}} \right)^2 \times \psi^*$$

PASS — Number of iteration passes through the cycle calculations required to complete a cycle match

R_D — Turbine design expansion ratio

R_e — Turbine expansion ratio

WF — Engine total fuel flow rate

SFC — Engine specific fuel consumption

η — Efficiency

$\Delta H/\theta_{cr}$ — Enthalpy change across the turbine corrected by turbine inlet theta-critical

ϕ — Afterburner inlet parameter, a function of inlet temperature, pressure, velocity, and burner length

SUMMARY

This report presents the final results of Regression Simulation of Turbine Engine Performance - Task I.

A baseline parametric turbojet simulation program was used to evaluate six alternate calculation procedures. These procedures, as developed, are general in nature and could be used in other similar gas turbine performance programs. There are always many ways of reducing run cost of any specific computer model. However, the following six areas were selected for study due to their general application and because analysis of a baseline computer run showed these areas to be major factors in computer run time.

THERMO PROPERTIES

The generation of thermodynamic properties of the gas path required by many of the component calculations was improved in two ways. The polynomial equations were shortened from fifth to third order with the number of temperature ranges increased to maintain accuracy. All iterations were replaced by direct equations.

MATRIX COEFFICIENT PREDICTION

The baseline program uses a typical finite difference method to generate the matrix of partial derivatives to begin the cycle matching procedure on each off-design data point. This was replaced by constants and curve fits of a sample data set to rapidly initialize the matrix, thus reducing the number of passes through the cycle calculations per data point.

TURBINE MAP REGRESSION

The baseline program uses turbine flow and efficiency characteristics in tabular form. Table interpolation was replaced by regression models of an alternate turbine characteristics format.

AFTERBURNER CALCULATIONS

Temperature rise tables were replaced with equations using a special set of thermodynamic properties which include dissociation effects. The calculations for pressure loss due to heat addition were replaced with a regression model.

COMPRESSOR MAP REGRESSION

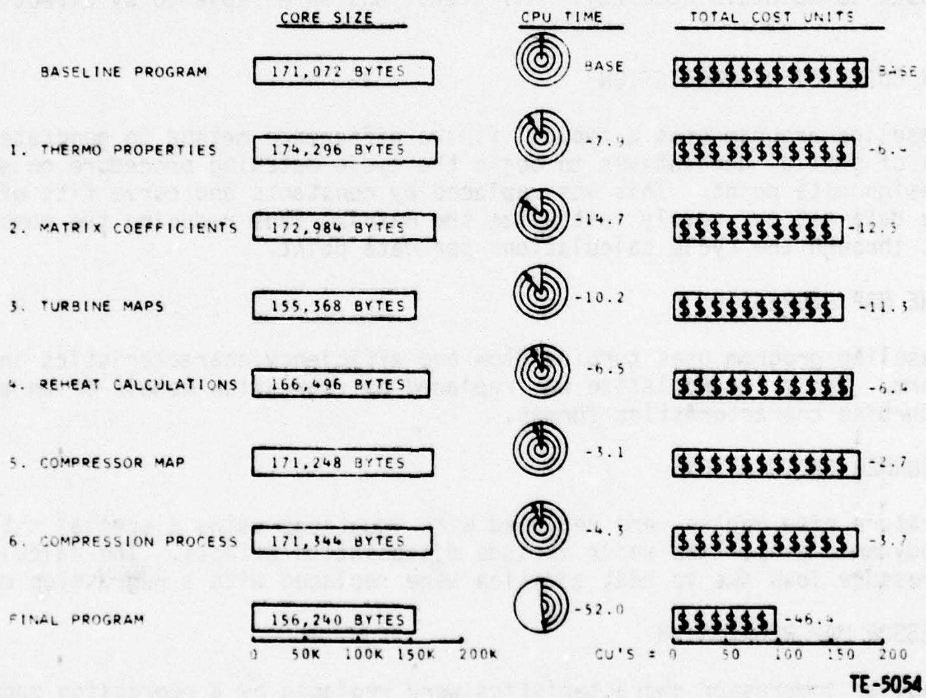
The tabular compressor characteristics were replaced by a regression model.

COMPRESSION PROCESS REGRESSION

The calculation of ideal enthalpy rise using thermodynamic properties and relative pressure function was replaced by a regression equation as a function of compressor inlet temperature and compressor pressure ratio.

The cost analysis was based on a charging algorithm which computed Cost Units (CU's) as a function of program core memory (CM) size and central processing unit (CPU) computing time. The following figure shows the final evaluation

results for each alternate procedure studied individually and for all procedures studied collectively. It shows that the final effect of this project is a cost reduction of 46.4% in the generation of parametric engine off-design performance data (which could have saved an estimated $9280 on computer charges during the development of a TEVCS data base in 1976).



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RSTEP Cost Reduction Summary.

SECTION I

INTRODUCTION

Regression Simulation of Turbine Engine Performance (RSTEP) was a four task program aimed at reducing the cost of using the Turbine Engine Variable Cycle Selection (TEVCS) and Airplane Responsive Engine Selection (ARES) procedures while maintaining or improving accuracy levels necessary for a meaningful propulsion concept and/or cycle selection. Detroit Diesel Allison (DDA), Division of General Motors Corporation, was awarded a contract for Task I of that program. This is the final report of Task I.

The purpose of RSTEP-Task I is to identify and evaluate computation procedures that will reduce computer resource expenditures where these new procedures are applied to existing parametric turbine engine performance programs. The program approach has been to define, develop and evaluate six alternate computational procedures first individually and then collectively in an existing parametric turbine engine performance program.

A Problem Program Efficiency Product leased from Boole and Babbage Inc., referred to hereafter as the PPE Analyzer, was used to identify the areas of the program of highest compute time and to evaluate compute time effects of program changes. DDA carefully coordinated the selection of alternate calculation procedures with the Air Force and evaluation results were frequently reviewed jointly to achieve a maximum benefit from this Task I effort. Although the alternate calculation procedures were developed specifically for parametric turbine engine performance programs, some may also be applicable to other turbine engine customer card decks and several could be used cost effectively in in-house turbine engine design programs as well.

Since the procedures developed in this RSTEP project were to be applicable industry wide, some areas of the baseline parametric deck were not considered for alternate procedures. These included table interpolation and the scheduling of variable geometry components. The present needs and methods in areas such as these vary greatly in the industry and, therefore, alternate procedures would not be generally adaptable. However, the basic methods of thermodynamic properties generation, component simulation and cycle matching do have enough commonality for industry acceptance of alternate procedures. It is in these areas that this RSTEP effort is primarily concentrated.

Regression analysis used in this project involved a stepwise multiple linear regression analysis program. This program has been in use a long time at DDA and uses procedures typical of most regression analysis computer programs found in the industry. The user identifies the desired independent variables as combinations of supplied parameters with which to correlate a dependent variable in a stepwise manner of adding independent variables to the equation one at a time. Weighting of data points is also permitted. Improvements in curve fitting accuracy often come from trying new and sometimes unusual combinations of independent variables involving cross-products and exponents. This type of regression analysis was utilized throughout this project.

SECTION II

EVALUATION PROCEDURE

It was considered important to define an adequate evaluation procedure to quantitatively assess the merits of each alternate procedure developed. The first step was to establish a baseline parametric deck and baseline data set with which to perform comparisons. Then an acceptable method of comparison and the evaluation criteria were established which included sufficient evaluation factors to provide guidance during alternate procedure development and to provide data upon which to make the selection of acceptable procedures for use in future parametric decks throughout the industry.

BASELINE PARAMETRIC DECK

The parametric steady-state design/performance deck selected as the base-line evaluation tool was used to generate the engine matrix performance data for the TEVCS Phase II study and for an ARES data base and ATS studies. It represents a family of advanced technology variable geometry afterburning turbojet engines consistent with component technology of the 1980/85 period and intended for use in advanced supersonic aircraft system studies. Parametric deck data represents "typical" engine characteristics for the engine design variables of overall pressure ratio (R_C), maximum turbine rotor inlet temperature (RIT) and an airflow scheduling parameter, theta break (θ_B). This parametric deck performs the engine matching and performance calculations in a manner typical of that used in the industry. Thus, it is used as a valid candidate for alternate procedure evaluation.

PPE ANALYZER

One fully-automated step in the evaluation process was the use of the Problem Program Efficiency (PPE) Product, a program leased from Boole and Babbage, Inc., which determines the areas where a program spends its time while in execution. Execution time is increased no more than five percent while accumulating over 11,000 samples of execution addresses and providing reports on statistical analyses of that data.

This analysis also provides a more accurate total CPU time than the one provided by the normal computer accounting system. The normal system may be as much as 20 to 30 percent low on CPU time for a multi-processing system due to a low sampling rate used to minimize overhead costs. The PPE Analyzer uses a wall-clock short sampling time interval. Thus, the ratio of active to total samples multiplied by the elapsed wall-clock time gives a much more accurate (though not perfect) total active CPU time with normal errors being less than five percent.

The analyzer was linked to the parametric deck for the baseline run and for the full evaluation of each alternate procedure and the final combined procedures program. Additional use of the analyzer was made in several alternate procedures where more than one approach was developed. It was also used to re-establish the baseline when changes were made in the computer hardware/software so that all comparisons could be correlated back to the same original baseline--making all data shown in this final report correspond to a common base.

In the baseline computer run, table interpolations required the highest percentage of compute time (32.12%), followed by calculation of thermodynamic gas properties (25.92%) and math functions (15.72%). The rest of these CPU time breakdown figures are shown in Table 14 along with a comparison to alternate procedure evaluation runs.

COST ALGORITHM

It was recognized at the start of this project that each computing center throughout the industrty uses a different cost algorithm and that the one used for cost reduction in this project could impact the results of the evaluations. Therefore, an airframe industry survey was made to arrive at a computer charging algorithm typical in the use of parametric decks. This survey resulted in several factors relevant to establishing a representative algorithm for this project.

- The majority of parametric deck User's run them on CDC equipment, primarily CDC 6600 computers.
- The majority of industry runs involve the creation of large data bases which result in primarily CPU-bound running with peripheral and I/O charges being a low percentage (10 to 20 percent) of the total run cost.
- Although the cost for core memory use on a CDC computer makes up a relatively high percentage (25 to 50 percent) of computer run cost, the trend at some facilities is to reduce that percentage.
- Charging methods and terminology vary with data centers. All facilities surveyed apply a dollar value to cost units applied to each type of computer operation performed. Therefore, in RSTEP the term cost unit (CU) will be used to compute the cost of evaluation runs. Major charges are for the central processing unit (CPU) which performs calculations and is charged for its usage time, or CPU seconds. Since all facilities use a sharing system, it is important to charge for the use of core memory (CM) only for the useful time, CM seconds.

Peripheral charges were a part of the run cost at all facilities surveyed. Therefore, it is a part of the RSTEP charging algorithm. However, the use of peripherals was not expected to change during the RSTEP program modifications since I/O per data point and the data packages were not changed and program overlay was not utilized. In light of this information, it was decided that the amount of CU's for CPU and CM portions of the baseline run be increased by 15 percent and that this same number of CU's be added to all evaluation runs to account for peripheral charges without individually bookkeeping disk/tape and I/O operations. This approach acknowledges the relative impact of peripheral costs on the RSTEP evaluation process without attempting to apply any one data center cost algorithm in detail.

This leaves only CPU time and CM time to be affected by and analyzed for RSTEP alternate procedures. Some facilities use a multiplying effect of CPU and CM time to compute cost units while others use an additive effect. It was decided that an additive effect be used such that CPU effect outweighs CM effect on the baseline run by a factor of two to one. Assuming that one second of CPU time is equal to one CU, then the use of core memory of a size equivalent to the baseline parametric deck for one useful second would produce a charge of 0.5 CU. Thus, the total cost for the baseline run for one second of CPU time is one cost unit for the CPU and 0.5 CU for the core memory.

Based on that information and on the baseline evaluation computer run discussed later in this section, the equation established for cost evaluation, using 23.77 cost units for the fixed charges for peripherals, is shown below.

$$\text{Total CU's} = 23.77 + \text{CPU} \times (1.0 + 0.5 \times CM/CM_{base})$$

Where: CPU is seconds of compute time
CM is core memory
CM_{base} is core memory of the baseline program

ACCURACY EVALUATION

The most important aspect of evaluating alternate procedures was the analysis of differences in engine performance resulting from the program changes. An essential part of this phase was automation. The goal was to use the major portion of resources for developing alternate procedures and to keep the evaluation process inexpensive and rapid but thorough.

To achieve this goal, the parametric deck generated a two-card output on each off-design data point which were automatically accumulated and stored on a permanent computer disk file on each run, requiring no card handling and providing data for a separate program to read and compare. The data on these cards included identification parameters such as data point number, altitude, flight velocity and power lever angle as well as engine performance parameters of not only net thrust and fuel flow rate but also 13 other engine performance parameters and the cycle matching iteration counter referred to as PASS.

Two baseline data sets were generated for evaluation, a checkout data set and a full evaluation data set. Figure 1 shows the engine operating conditions used for logic checkout for each of four engines in the full evaluation data set. The checkout data set consisted of the same 185 data points but for only the second engine. The four engines were selected to include changes in the independent design variables (R_C, RIT and θ_B) in the evaluation process. The operating conditions were selected to represent a typical advanced supersonic aircraft flight envelope with non-augmented power (PLA $\leq$ 50) extending only to Mach 1.2 and augmented power (PLA > 60) going up to Mach 2.5.

An accuracy evaluation computer program was then written to perform the accuracy portion of the evaluation process on both the checkout and full data sets. It retrieved the baseline data set and any other specified data set from disk files and, based on a set of input instructions, analyzed the performance of each engine as well as producing a summary of all four engines. It permitted the user to select different groups of data points to be analyzed and the performance parameters to be compared. Job control language (JCL) was set up to execute this accuracy evaluation immediately following the execution of the data package on the same computer run which eliminated some card handling and provided rapid evaluation results.

Guidelines were established as to acceptable variations in engine performance resulting from program changes. The primary concern is that alternate procedures should maintain consistency between configurations such that trends relative to the key variables are not significantly affected. There may be some areas of engine operation, such as low power settings, where variations of

several percent could be acceptable without affecting trend consistency in parametric studies. However, goals for individual alternate procedures were set at 0.5% average and 1.5% maximum deviations in net thrust and fuel flow rate with rejection levels set at 1.0 percent average and 3.0 percent maximum deviations.

BASELINE COMPUTER RUN

A baseline was established with which to compare checked out alternate procedures. It involved the execution of the 740-point full evaluation data package with the baseline program linked to the PPE Analyzer. The baseline program size was 171,072 bytes on an IBM 370/168 computer. The PPE Analyzer accumulated 11,040 active samples taken during execution, giving a 96 percent confidence level that the percentage of compute time breakdown is within 0.8 percent.

The baseline computer run required 105.65 seconds of CPU time. This gave the following cost units for CPU time and core memory.

$$\begin{aligned} \text{CU's for CPU and CM} &= 105.65 \times (1.0 + 0.5 \times \text{CM}/171{,}072) \\ &= 158.48 \text{ CU's} \end{aligned}$$

The previous discussion of cost algorithm indicated that 15 percent of this cost unit figure on the baseline run would establish a fixed assessment for peripheral usage on all evaluation runs.

$$\text{CU's for peripherals} = 0.15 \times 158.48 = 23.77 \text{ CU's}$$

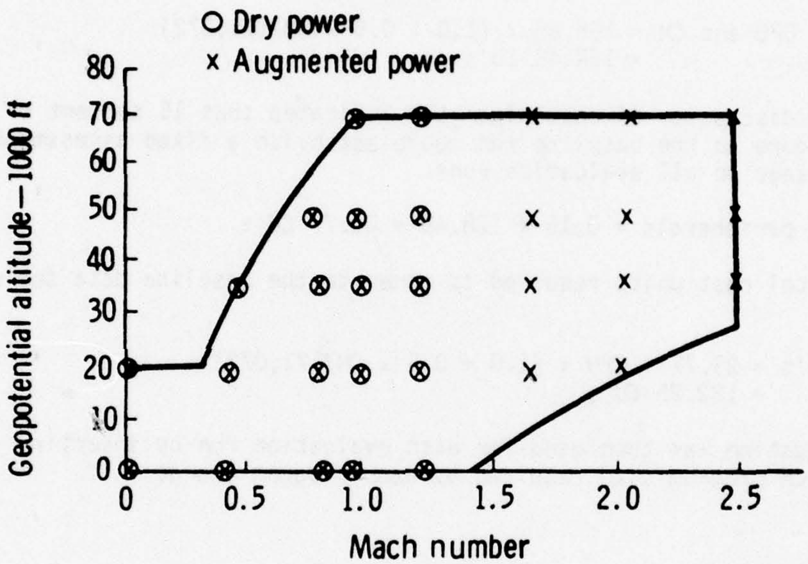
Thus, the total cost units required to generate the baseline data set was calculated.

$$\begin{aligned} \text{Total CU's} &= 23.77 + \text{CPU} \times (1.0 + 0.5 \times \text{CM}/171{,}072) \\ &= 182.25 \text{ CU's} \end{aligned}$$

This same equation was then used for each evaluation run by inserting the CPU seconds and CM program size required by each program change.

Four Engine Cycles:

No.	R_C	T_4 (°F)	θ_B
1	9	2350	1.00
2	12	2700	1.12
3	15	3050	1.24
4	18	3400	1.36



Dry Power Data: 5 throttle setting at each of 19 flight conditions; total of 95 pts.

Augmented Power Data: 3 throttle settings at each of 30 flight conditions; total of 90 pts.

Number of data points per engine: 185 pts.
Number of data points for evaluation process: 740 pts.

Note: Scheduling of variable geometry components would remain the same throughout the task to maintain comparability.

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Figure 1. Evaluation Data Package.

SECTION III

FIRST STUDY--THERMO PROPERTIES

Preliminary studies indicated that approximately 25 percent of the compute time was spent in the generation of thermodynamic properties performed within a generalized function subprogram, called Function GASP for gas properties. This routine is treated like a utility routine which readily provides one of ten thermodynamic state properties on call from anywhere within an engine model. Because of its high usage, the GASP routine was a very good candidate for cost reduction effort.

The routine used in the baseline program contains fifth-order polynomial curve fits (one for each of three temperature ranges) to define enthalpy and relative pressure function logarithm as functions of temperature and fuel-air ratio. Other parameters are computed using these polynomials coupled with equations and, in some cases, an iteration procedure. Polynomials are used for air and stoichiometric combustion products, and a mole fraction equation is used to interpolate for less than stoichiometric fuel-air ratios. The three temperature ranges covered 300 to 1000, 1000 to 2400, and 2400 to 4500 degrees Rankine.

STUDY PLAN

<u>Program area affected:</u> Function subprogram GASP.

<u>Goals:</u> (a) Remove all iterations.
(b) Replace calculation of Cp and h-lambda with direct curve fits.
(c) Replace the three temperature ranges of fifth-order polynomials with four ranges of third-order polynomials.

<u>Step 1:</u> Select the four temperature ranges.

<u>Step 2:</u> Using the baseline GASP routine, generate data points to be used in computing polynomial coefficients.

<u>Step 3:</u> Compute the third-order polynomial coefficients using four points so that the polynomial equation passes through the points. Where two temperature ranges must meet, a common point is used in both equations.

<u>Step 4:</u> Modify the GASP routine to incorporate the new equations. Replace iterations and the Cp and h-lambda calculations with direct equations while maintaining the same calling sequence of the routine.

<u>Step 5:</u> Write a simple program to call the old and new versions of GASP covering all variables and full ranges of temperature and fuel-air ratio. Print percent deviations for study and guidance. Repeat steps necessary to achieve desired accuracy.

<u>Step 6:</u> Check out in baseline parametric deck.

<u>Step 7:</u> Perform final evaluation.

DISCUSSION OF EFFORT

Since the new routine was to be compared to the baseline routine, the baseline GASP routine was used as the source for data to generate new polynomials as opposed to going back to its original source of mixing ideal gases. It was soon found that the selection of temperature ranges and the selection of the two intermediate temperature points within each range had a significant effect on accuracy. After several check runs, the four temperature ranges were selected, in degrees Rankine, as 350 to 800 (allowing extrapolation to 300), 800 to 1550, 1550 to 2750 and 2750 to 4300 (allowing extrapolation to 4500). Even spacing of points within a temperature range was found to be as good as an "increasing delta" approach which was also tried.

The development of the original polynomials showed a greater difficulty in curve fitting the lower temperature range since the temperature-enthalpy curve has more curvature at lower temperatures and tends to straighten at higher temperatures. For this reason the temperature range of each polynomial increased as temperature increases. This kept curve fitting errors generally less than 0.01 percent.

The calculation of the polynomial coefficients was done in double precision following some accuracy problems with single precision calculations. However, the coefficients are then used in single precision in the GASP routine.

Accuracy problems were encountered in correlating phi (the natural logarithm of the relative pressure function) with temperature and enthalpy. In those troublesome areas the temperature and enthalpy values were taken to the 0.1 power, which tended to minimize the error more than other exponents studied. A study of the listing of the new GASP routine in Appendix A will identify when this exponentiation was used.

The major problem encountered in this study involved the direct calculation of parameters where iterations were used in the baseline routine. The interpolation for fuel-air ratios between zero and stoichiometric involve an equation based on mole-fractions at a temperature. This equation is used when temperature is known and phi or enthalpy is desired. However, interpolation in the reverse direction becomes more complex. Following several attempts to derive acceptable interpolation equations for these situations, the final solution was to curve fit the interpolation ratio as a function of the two independent variables fuel-air ratio and either phi or enthalpy. These equations can be found in the listing in Appendix A.

The specific heat at constant pressure (Cp) was incorporated by equations where it had been computed in the baseline routine via the enthalpy equations and an increment (plus and minus three degrees) in temperature. The h-lambda term used in burner calculations to adjust fuel heating value is a temperature-enthalpy function. It had been computed using the temperature-enthalpy polynomials for air and stoichiometric products. In the new routine the polynomials were added to directly compute h-lambda from temperature.

OTHER ROUTINES STUDIES

Five other versions of the GASP routine were given a cursory evaluation to be certain that something obvious was not being overlooked. Since the baseline routine did not include extra logic for such additional independent variables as dissociation effects, water vapor effects and the ability to vary fuel hydrocarbon ratio, these features were not made a part of this study even though some versions contained one or more of these options.

Version "A" utilized simple equations derived through regression analysis which were developed for possible use in hybrid computers. Version "B" contained more complex regression equations covering the full temperature and fuel-air ratio ranges in one equation for use on small-core computers for program logic checkout. Version "C" used the equations and logic of the 1967 version of the AFAPL "SMOTE" program. Version "D" used a method typical of a 1971 era parametric deck. Version "E" was assembled using the thermo properties routine of the program NNEP acquired from NASA-Lewis Research Center but originally developed by Mr. Caddy of NADC, Warminster, Pa.

Versions "A" and "B" contained simplifications not suitable from an accuracy viewpoint. Versions "C", "D", and "E" were accurate enough but lacked the desired speed (Table 1). Versions "C" and "D" relied primarily on eighth-order polynomials to cover the entire temperature range. Version "E" essentially uses a series of spline fit coefficients rather than polynomial curve fits.

Since these routines had to be adapted to the baseline parametric deck, some conversion penalties were unavoidable. However, the results of their evaluation using the checkout data set were considered sufficient to support the direction of effort taken to speed up the GASP routine. Table 1 summarizes the results of comparing each of the five routines to the baseline program routine. These results supported the original planned effort.

TABLE 1
RESULTS OF OTHER GASP ROUTINES

	Percent Changes		
	ΔCPU time (minus is faster)	Avg ΔFN	Avg ΔWF
Version A	-10.9	4.9	7.0
B	+ 3.6	1.8	2.7
C	+12.2	0.2	0.2
D	+32.4	0.1	0.1
E	+ 9.9	0.3	0.2

FINAL RESULTS

The new routine was checked out in the baseline program. Accuracy levels were improved to acceptable tolerances and compute time reduction was substantial. Then, the full evaluation run was made. The following table shows the accuracy results of the 740 data point comparison.

TABLE 2
THERMO PROPERTIES ACCURACY DATA

Engine	Average Deviation - % 1	2	3	4	All	Maximum Deviation - % 1	2	3	4	All
FN	0.12	0.07	0.07	0.07	0.08	0.38	0.46	0.25	0.35	0.46
WF	0.13	0.07	0.08	0.07	0.09	0.53	0.29	0.32	0.35	0.53
SFC	0.08	0.04	0.04	0.04	0.05	0.33	0.25	0.20	0.13	0.33
PASS	-6.7	-2.2	-6.7	-5.1	-5.2	73.3	100	-66.7	-60.7	100

The accuracy of the new routine is well within acceptable tolerances for all data points. The removal of iterations within the GASP routine appears to have improved the cycle matching iteration convergence rate slightly (PASS was reduced by 5.2 percent). The detailed breakdown of CPU time within the program is summarized in a later section. It shows the time spent in the thermo properties routine reduced to nearly half with extra time used for exponentials.

As shown in Figure 1 of the Summary, core memory was increased due to the addition of several polynomial equations in the GASP routine. The CPU time was reduced by 7.9 percent for a final cost reduction of 6.4 percent, as shown in the Cost Unit equation.

$$\text{Total CU's} = 23.77 + 97.33 \times (1.0 + 0.5 \times 174{,}296/171{,}072)$$
$$= \underline{170.68} \text{ CU's}$$

Appendix A is a listing of the final Function GASP subprogram developed for RSTEP. A detailed study of that listing will provide more information on the equations and logic used than is possible to describe in this text.

SECTION IV

SECOND STUDY--MATRIX COEFFICIENTS

The most obvious approach to reducing the compute time in engine simulations is to reduce the number of passes through the cycle calculations required to balance the component flow rates and shaft horsepowers. A procedure which accomplishes this has no accuracy problem since cycle calculations and matching tolerances are unaffected. The number of iteration passes can be divided into two categories: (1) those required to generate the partial derivatives by the finite difference method to set up the Newton-Raphson matrix and (2) those required to converge the cycle balance to be within acceptable tolerance. The second portion, the iteration passes, is a function of the iteration procedure which has been improved and re-examined frequently by the industry. Therefore, a plan was established to eliminate the passes required to compute matrix coefficients by substituting a matrix coefficient prediction procedure. (See Appendix B for definition of coefficients.)

It should be obvious that any cost reduction shown by this study will be considerably greater when applied to more complex cycles. The cycle used in this study involves only four independent variables, thus only four extra cycle passes are required using finite differences to establish the matrix coefficients. For more complex cycles (turbofan and variable cycle engines), the number of independent variables may be double, triple, or more. As these extra cycle passes become a higher percentage of the overall compute time, their elimination will produce a greater cost reduction.

STUDY PLAN

<u>Program area affected</u>: The beginnning of a match point calculation.

<u>Goal</u>: Replace the finite difference method of computing linear partial derivatives with a prediction method for establishing those same matrix coefficients. In the baseline parametric deck this would theoretically reduce the number of cycle calculation passes by four.

<u>Approach</u>: It was recognized that the most desirable approach would be to derive equations for the first derivative of the relationships between the independent and dependent variables. However, it was found that for the turbojet cycle of the baseline program this approach became beyond the scope of the project. Therefore, the approach selected for evaluation was an empirical one.

<u>Step 1</u>: Generate a data file containing all matrix coefficients and related cycle data for each of a representative set of matched data points.

<u>Step 2</u>: For each matrix coefficient, compute the average value and the average and maximum deviation based on the data sample.

<u>Step 3</u>: For those coefficients with relatively high variation, generate regression equations to correlate them to cycle variables.

<u>Step 4</u>: Incorporate logic into the parametric deck to initialize the matrix coefficients between the first cycle calculation pass and the first Newton-Raphson matrix solution. The regression equations are used for coefficients of high variation and the average values used for those of low variation.

Step 5: Check out the procedure and improve regression equations as necessary.

Step 6: Perform final evaluation.

DISCUSSION OF EFFORT

The baseline parametric deck bypasses the generation of matrix coefficients on partial augmentation data points when preceded by a maximum augmentation data point at the same flight condition. Those data points use the coefficients from the previous data point and will not be affected by a coefficient prediction procedure.

A total of 518 data points were selected from the full evaluation data package as the data sample on which to base the prediction method. This selection of a data sample represents a typical approach to be used in the final preparation of any engine simulation following completion of component definition and engine control characteristics. Minor changes in engine characteristics at a later time should not significantly reduce the effect of the coefficient prediction method.

The first analysis of the 518-point data sample revealed the need to separate the points into two groups--a high throttle group and a low throttle group. This is caused by the variable geometry turbine being used to vary turbine flow capacity in the high throttle region and then being held at the low-flow position in the lower engine throttle range. This type of regional grouping is a function of engine design and control and should be studied when developing a prediction procedure on each new parametric deck.

The division of the data sample was made with 364 data points at or above a power lever angle of 40 and 154 data points below that throttle setting. New average values and average and maximum deviations were computed for each data group. From this statistical data, several coefficients were selected for regression curve fitting based on either having high variation (above 20 percent) or changing sign since a coefficient with a wrong sign can be worse than one being of the wrong magnitude. The rest were initialized to their average values.

Regression analysis was used to curve fit each of the selected coefficients as a function of related cycle variables. Equations using a low number of terms as well as more complex regression equations were developed to study their effect on the rate of cycle matching convergence. To study these effects, three procedures were individually evaluated in the parametric deck:

1) Using only average value
2) Using the equations of low complexity
3) Using the equations of higher complexity

The use of only the average values for the coefficients was unsatisfactory. The use of regression equations of low complexity (fewer terms) coupled with average values for some of the coefficients was found to be adequate. The use of more complex regression equations required more manpower to develop and could not be justified.

Therefore, the final checkout was made using the combination of constants and simple regression equations shown in Appendix B. The regression equations required parameters provided by either the engine design, the engine operating condition, or the first pass through the cycle calculations based on the initial values of the cycle's four independent variables. This matrix prediction procedure was relatively easy to program into the parametric deck.

ANOTHER APPROACH STUDIED

Some programs provide an automatic incrementing option which permits the reuse of the matrix coefficients through an orderly change of power lever angle.

The baseline RSTEP parametric deck was modified to use previous matrix coefficients below a power lever angle of 50.0 (below maximum non-augmented power). The full evaluation data package was executed without the PPE Analyzer for a quick evaluation of this simulation of an automatic incrementing option. The computer's CPU timer showed a slight loss in compute time of 1.2 percent with no significant change in engine performance.

The statistical analysis data from that computer run shows why the automatic incrementing mode fails to achieve the desired results. The average number of passes was reduced at higher power settings as would be expected, but increased rapidly at lower power settings.

TABLE 3
AUTOMATIC INCREMENTING CHECK

PLA	Average PASS Baseline	Average PASS Auto. Incr.
45	10.09	7.04
40	12.57	7.96
31	10.25	21.54
22	11.97	13.22

There are several factors affecting this, such as variable geometry scheduling and operating on a different control schedule below 40.0 power lever angle. The major point to be made is that the automatic incrementing mode used in some programs must be a special option switched on at the discretion of the User and its effectiveness is reduced by certain engine types and cycle matching methods. Quite the opposite is true with the predictor method when properly implemented. It works at all power settings and flight conditions, requires no User selection and contains coefficients to handle all modes of cycle matching used in the program. Thus, even if automatic incrementing does save compute time in most programs, the coefficient predictor method development effort is well justified for high-usage steady-state engine models.

FINAL RESULTS

The final check run showed nearly the improvement expected (a reduction of four passes per data point). Thus, the full evaluation was made. The following table shows the accuracy results of the 740 data point comparison to the baseline program.

TABLE 4
MATRIX COEFFICIENTS ACCURACY DATA

Engine	Average Deviation - % 1	2	3	4	ATT	Maximum Deviation - % 1	2	3	4	ATT
FN	0.05	0.05	0.05	0.04	0.05	0.20	0.27	0.31	0.35	0.35
WF	0.05	0.05	0.05	0.05	0.05	0.27	0.25	0.26	0.26	0.27
SFC	0.03	0.03	0.03	0.03	0.03	0.14	0.18	0.23	0.13	0.23
PASS	-19.9	-14.2	-24.2	-21.7	-20.0	200	300	150	133	300

The deviations in engine performance observed in this evaluation are merely the result of slightly different matching within the same tolerances. The average data point matched in fewer iteration passes, but some data points showed an increase in the counter. This is expected to occur with any matrix coefficient prediction method. The average reduction in the iteration counter should improve slightly as the engine cycle, hence the matrix size, becomes more complex such as a two-spool turbofan cycle.

As shown in the figure 1 the summary, core memory increased slightly due to the storage of the average matrix coefficients and the addition of the regression equations. The detailed breakdown of CPU time in Table 14 shows no significant shifting in effort within the program, which is expected when only the matching convergence rate is altered. The CPU time was reduced by 14.7 percent for a final cost reduction of 12.5 percent, as shown in the Cost Unit equation.

$$\text{Total CU's} = 23.77 + 90.12 \times (1.0 + 0.5 \times 172{,}984/171{,}072)$$
$$= \underline{159.45}\ \text{CU's}$$

Appendix B shows the logic required to make the matrix coefficient predictions. The development of the data base for establishing the constants and equations requires little effort beyond the normal checkout of a program. The complexity of the logic and regression equations is largely dependent on the complexity of the cycle and control scheduling. All things considered, the effort required to implement such a procedure should be relatively low (as indicated in Table 13) with substantial cost reduction potential. A major advantage is that there is no risk of sacrificing accuracy to achieve these gains.

SECTION V

THIRD STUDY--TURBINE MAPS

The baseline program compute time breakdown showed that table interpolations consumed nearly one-third of the CPU seconds. Examination of the program pointed toward the turbine maps as being the most complex tables in the program. Since the cycle involves a variable-area (variable flow capacity) turbine, the turbine characteristics are in layered map form to represent a range of turbine area settings. To represent a range of turbine designs to cover a parametric family of engines, two complete sets of turbine characteristics are contained within the program--one set for a single-stage turbine and another set for a two-stage turbine. The tables include corrected flow and efficiency as functions of a non-dimensional form of expansion ratio, corrected speed and turbine area setting. The non-dimensional expansion ratio is a function of the operating expansion ratio and the design expansion ratio for any individual engine, which requires it to be scalable for a range of design expansion ratios.

This alternate procedure involved the study of turbine characteristics for the explicit purpose of reducing the time required to compute turbine performance without having a major impact on the difficulty to integrate turbine performance into engine programs or on the accuracy of those turbine characteristics. A secondary potential gain of this alternate procedure was a reduction in program size due to replacing part, or all, of the turbine map tabulations with curve fit coefficients.

STUDY PLAN

Program area affected: Calculation of turbine flow capacity and efficiency.

Goal: To reduce the compute time required to generate turbine performance.

Approach: Investigate regression modelling of the present and alternate turbine characteristics formats to eliminate tabular data - a major consumer of computing time.

Step 1: Write a separate turbine map evaluation program. This consists of a mainline program which compares table look-up results with an alternate method.

Step 2: Define a matrix of turbine map input data which will fully exercise any new format.

Step 3: Develop a regression model of the present format and evaluate in the program of Step 1.

Step 4: Develop a regression model of a work parameter to replace efficiency and evaluate in the program of Step 1.

Step 5: Develop a regression model of a psi/psi* format for efficiency and evaluate in the program of Step 1.

Step 6: Select the method(s) of Steps 3, 4 and 5 which demonstrate acceptable accuracy levels and adaptability to parametric decks. Integrate each into the baseline program and check out.

Step 7: Select the best method and perform a full evaluation.

DISCUSSION OF EFFORT

A simple evaluation program is essential to rapidly compare alternate methods to the one presently used to provide turbine performance characteristics. This separate program was written and proved to greatly expedite the evaluation of each alternate method and is a good test as to a method's ease of integration into a parametric deck. The mainline program developed used a data matrix of 1728 data points which encompassed all types of turbine map usage required by the baseline parametric deck.

Two sets of turbine characteristics are included in the baseline parametric deck - a set for a one-stage turbine and another set for a two-stage turbine. Both sets were studied in this alternate procedure development. Each set contained flow and efficiency as functions of expansion ratio, corrected speed and turbine area setting as a percent of design area. A multi-line (bi-variate) table was used for each of several area settings with second-order interpolation used along each line, between the lines and between the area setting layers.

The turbine flow maps were replaced by the subprogram Function WTURB. This routine contains regression equations for each turbine area setting and interpolates between settings similar to the table interpolation routine. For each area setting a regression equation is used to define the choking expansion ratio as a function of rotor speed. These sometimes required more than one equation. Then a regression equation is used to define flow as a function of expansion ratio, choked expansion ratio and speed in the unchoked region and only as a function of speed in the choked region.

One special measure was taken in curve fitting each flow map. First, the unchoked flow portion was curve fit. Then, using a simple computerized iteration, the equation was used to compute the expansion ratio at which the equation gave the choked flow value at each turbine speed. This was done for two reasons. First, there was no tabulated map point which represented the exact choke point on each speed line and second, it is desirable to make the curve fit equations for the unchoked and choked regions as equal as possible at the choke point. The choking expansion ratio values from these unchoked equations were used to curve fit the choke point expansion ratios. This caused the unchoked flow equations to agree with the choked flow values within the accuracy of the two curve fits. This approach appears to provide sufficient continuity across the choke point so as to not create cycle matching convergence problems which would occur from a flow discontinuity. Checkout of this method proved good enough to use in the final evaluation.

Efficiency Map Regression

Preliminary study of the efficiency maps indicated that regression curve fitting of these maps would be difficult, time consuming and inaccurate and this approach was abandoned.

Delta Enthalpy Map Regression

Preliminary studies indicated that this would be useful in two ways. It would remove a table interpolation and would also reduce the use of thermodynamic

properties in the turbine routine. The alternate form was $\Delta H/\theta_{cr}$ which would provide turbine exit enthalpy without the use of the relative pressure function and efficiency. Turbine efficiency could then be computed separately after the cycle match if so desired. The data conversion was made with an assumed design expansion ratio (the original map is in non-dimensional form) and the new tables were plotted and curve fit. The regression equations were compared with the table and found to be reasonably accurate. However, when scaling of expansion ratio was implemented, the off-design performance could not be accurately scaled--even with a regression equation of a variable scale factor. It was concluded that this approach might be applicable to a specific turbine but not in a parametric model which requires a substantial range of design expansion ratios.

psi/psi* Map Regression

The efficiency tables were converted to a (psi/psi*) versus (psi/eff)/psi* form. Plots were made and found to be favorable for curve fitting all turbine area settings combined for each turbine design (one-stage and two-stage). Two sets of equations were tried, one set for accuracy having 14 complex variables and another set for speed having fewer and less complex variables. Compute time was not reduced as desired and deviations were somewhat high for both sets of equations. Therefore, regression equations were generated for each turbine setting separately using second-order interpolation between equations. This method was integrated into the baseline program and achieved the desired goals.

LINEAR INTERPOLATION TESTED

The baseline parametric deck was modified to use linear interpolation in the turbine map table look-ups instead of second-order interpolation. This was done in three steps: (1) linear along the lines, (2) linear along and across the lines and (3) linear between layers, as well as along and across the lines. This was applied to both the flow and efficiency baseline tabular maps. The following table summarizes the results.

TABLE 5
TURBINE MAP LINEAR INTERPOLATION RESULTS

Interpolation Order			Avg. Dev.		Max. Dev.		CPU Time
Re	Speed	Area	FN - %	WF - %	FN - %	WF - %	Reduction - %
1	2	2	0.092	0.098	0.617	0.463	0.5
1	1	2	0.245	0.149	-0.680	-0.858	2.1
1	1	1	0.342	0.160	-0.953	-0.867	3.0

This data indicates that linear interpolation in all directions of the turbine maps is sufficiently accurate for parametric decks and is also probably accurate enough for most gas turbine cycle programs provided the turbine maps are as thoroughly defined as they are in this parametric deck. As a result of this data, the interpolation between layered map regression equations was changed to linear interpolation for flow and psi/psi* form of efficiency.

FINAL RESULTS

The final flow and psi/psi* form of efficiency regression models were combined and integrated into the baseline parametric deck. Figure 2 below shows a graphical comparison of the original and final turbine efficiency forms. A full evaluation run was made on this program with the accuracy results shown in Table 6.

The removal of the turbine tables significantly reduced the program size and the regression equations were appreciably faster than the table interpolations, as shown in the Cost Unit equation.

$$\text{Total CU's} = 23.77 + 94.88 \times (1.0 + 0.5 \times 155{,}368/171{,}072)$$
$$= \underline{161.74}\ \text{CU's}$$

Of the 10 percent reduction in CPU time, approximately one percent is due to linear interpolation between map layers, based on the data of Table 5 (difference between 2.1% and 3.0%).

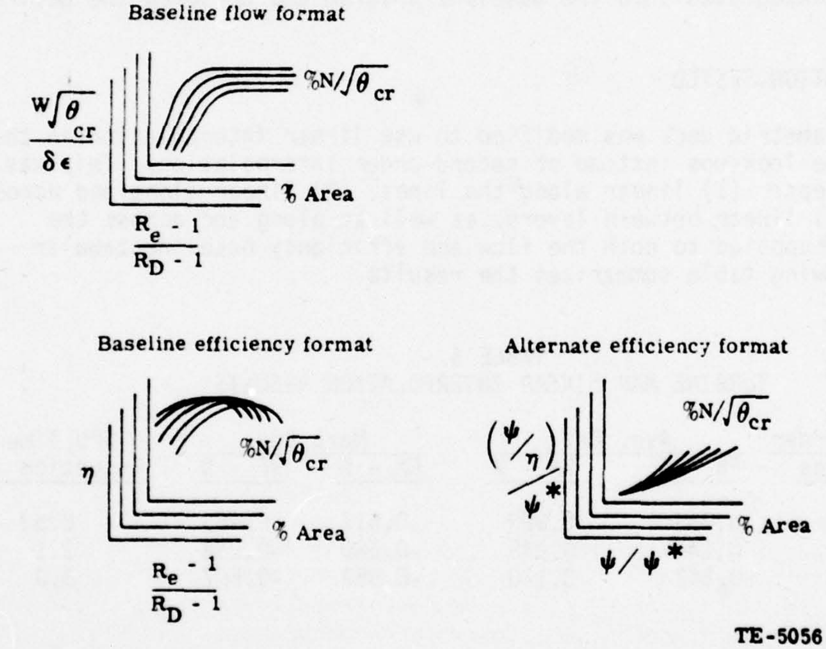


Figure 2. Turbine Characteristics Formats.

TABLE 6
TURBINE MAPS ACCURACY DATA

	Average Deviation - %					Maximum Deviation - %				
Engine	1	2	3	4	All	1	2	3	4	All
FN	0.46	0.44	0.39	0.38	0.42	1.25	1.25	1.06	1.09	1.25
WF	0.69	0.65	0.57	0.56	0.62	2.38	1.83	1.77	1.48	2.38
SFC	0.30	0.31	0.31	0.29	0.30	1.33	1.13	0.89	0.81	1.33
PASS	+6.5	+14.0	+5.2	+2.0	+6.9	200	400	300	100	400

The maximum deviations were in fuel flow rate, and they occurred when the turbine was in a partially open flow setting. This indicates that these errors are caused by turbine efficiency deviations caused by the combined effects of the altered efficiency format, curve fitting, and linear interpolation between area setting maps.

When the new efficiency map format was used in a tabular form (directly converted point by point), the compute time increased four percent due to the change to using phi. More extensive program changes could have nearly eliminated that four percent penalty. Therefore, the CPU time reduction due to regression modeling was actually the 10 percent shown in the cost unit equation plus four percent which was lost due to format change.

Appendix C contains listings of the single-stage turbine map regression model routines. These listings demonstrate the logic and equation complexity required to adequately model a set of variable geometry turbine characteristics. Turbine map regression is considered a worthwhile effort in situations where high usage is expected, program size is of concern, and/or time is available to develop the equations.

SECTION VI

FOURTH STUDY--REHEAT CALCULATIONS

The baseline parametric deck performs the major portion of the afterburner calculations only once per data point after the cycle is matched for non-augmented power. Therefore, any improvements in this area of calculations would prove even more valuable in a program which performed the reheat calculations within the cycle match.

The baseline program performs the major afterburner hot core calculations in the following manner.

- Cold pressure loss - the pressure loss before heat addition is a percentage of the dynamic head.
- Reheat efficiency - table including effects of fuel-air ratio and = f (temperature, pressure, velocity, burning length).
- Ideal temperature rise - temperature rise tables including effects of dissociation, pressure and fuel lower heating value.
- Pressure loss due to heat addition - momentum balance iterative calculations.

STUDY PLAN

Program area affected: Afterburner calculations.

Goal: To replace all tabular data with either regression equations or calculations and to replace the iteration in computing pressure loss due to heat addition with regression equations.

Approach: A set of thermodynamic properties was available which included effects of dissociation. For regression models, generate sufficient parametric temperature rise and pressure loss data to map afterburner performance characteristics.

Step 1: Curve fit the reheat efficiency table and check it out in the baseline program.

Step 2: Adapt the thermo properties routine which includes dissociation effects to the baseline program and modify the reheat temperature rise calculations to use those properties for the effects of dissociation.

Step 3: Parametrically generate sufficient reheat data to correlate temperature rise and pressure loss with all related independent variables.

Step 4: Using regression analysis, curve fit the parametric reheat data and integrate the resulting equations into the afterburner calculation subroutine of the baseline program.

Step 5: Execute check runs to evaluate combinations of the alternate thermo routines and the regression equations to select a method for final evaulation.

Step 6: Select the best method and perform a full evaluation. Also establish conclusions and recommendations concerning all methods developed.

DISCUSSION OF EFFORT

Of the four major areas of reheat calculations, the cold pressure loss was determined to have little potential for improvement and was not studied further. The reheat efficiency table was curve fit and incorporated into the afterburner subroutine. It was found to be acceptable in equation form and was used during the development of the other methods for this alternate procedure. The compute time was reduced only slightly by this change due to the removed table being a small one. The equation was of the following form:

$$eff^{*} = f(CF^{0.1}, CF^{2}, CF^{5}, CF*FAR7, CF*FAR7^{0.5}, FAR7^{1.5}, FAR7/CF, FAR7^{2}, CF*FAR7^{2})$$

where eff is burner efficiency
FAR7 is afterburner fuel-air ratio (reheat fuel flow rate divided by air available to burn)
CF is burner correlation factor (function of burner length, burner inlet temperature, pressure and velocity)

The change from temperature rise tables to the alternate thermo properties was achieved with little difficulty. An accuracy evaluation study showed performance deviations to be acceptable and caused by different dissociation effects being assumed in the development of those routines than were used in the temperature rise tables. Check runs indicated reductions in compute time on the order of five percent in the baseline program.

Figure 3 shows the ranges of independent variables used to define the afterburner parametric data to be used in curve fitting temperature rise and pressure loss due to heat addition. Two regression models were developed - short

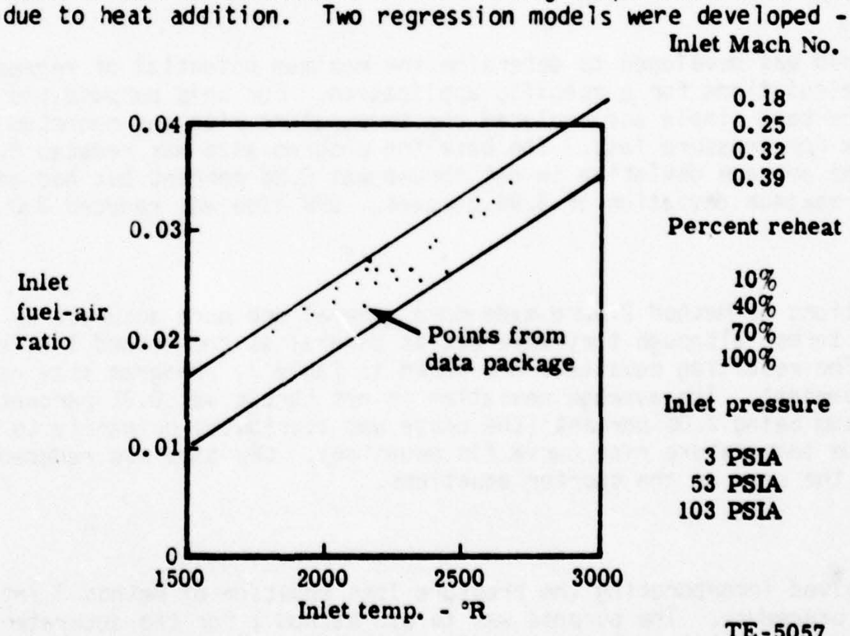


Figure 3. Afterburner Parametric Data.

*Note: Equation used only below a given value of CF. Above that CF, efficiency is a constant.

equations for speed and a set of more general equations. The short equations (having few coefficients) were developed using only the points from the data package. The more general equations used data generated to cover the full band width and range of independent variables of Figure 3.

A total of four alternate routines were studied involving the following combinations.

1) Temperature rise by thermo properties which include dissocation effects; pressure loss calculation unchanged
2) Shortest possible curve fit equations for both temperature rise and pressure loss
3) More general curve fit equations for both temperature rise and pressure loss
4) Temperature rise by thermo properties which include dissociation effects; pressure loss by regression equations

Method 1

This involved the use of the thermo properties as previously described. Program size was reduced 5.3 percent due to replacing the tables with calculations. The average deviation in net thrust was 0.30 percent with a maximum of 1.63 percent. Compute time was reduced 4.6 percent.

Method 2

This method was developed to determine the maximum potential of regressing the reheat calculations for a specific application. For this purpose the equations were kept simple and replaced the temperature rise and momentum balance iteration for pressure loss. The baseline program size was reduced 8.5 percent. The average deviation in net thrust was 0.28 percent but had an unacceptable maximum deviation of 3.94 percent. CPU time was reduced 3.0 percent.

Method 3

The equations of method 2 were made more general and more accurate by including more terms, although they were not as general as the method 1 calculations. The resulting equations are shown in Table 7. Program size reduction was 7.5 percent. The average deviation in net thrust was 0.21 percent with the maximum being 2.05 percent (the cause was attributed primarily to inaccuracy in the temperature rise curve fit equation). CPU time was reduced 3.0 percent, the same as the shorter equations.

Method 4

This involved incorporating the pressure loss equation of method 3 into the method 1 procedure. The purpose was to use method 1 for the accurate and fast temperature rise while getting benefit of the pressure loss regression equation. The program size was reduced 5.4 percent but CPU time was reduced 6.5 percent. The average deviation in net thrust was 0.31 percent with a maximum of 1.65 percent.

FINAL EVALUATION

Since the four methods showed similar improvements (within a few percent), the full evaluation data package and PPE Analyzer were used to evaluate each method. From these studies the fourth method was selected as the final alternate afterburner performance calculation procedure. Table 8 summarizes the accuracy data from the evaluation of that method.

TABLE 7
GENERALIZED REHEAT REGRESSION MODEL

Definition of Terms:

FARHC = Afterburner inlet fuel-air ratio
FAR7 = Afterburner exit fuel-air ratio (input)
H6HC = Afterburner inlet enthalpy, Btu/lbm
P6HC = Afterburner inlet pressure after cold loss, lbf/in^2
XM6 = Afterburner inlet Mach number
DHQH = Unadjusted reheat enthalpy rise divided by H6HC
DHQHA = Final reheat enthalpy rise divided by H6HC
X3 = FAR7 - FARHC
X5 = X3/FARHC
DPQP = Reheat pressure change divided by P6HC
P7HC = Afterburner exit pressure, lbf/in^2

Ideal enthalpy change equation:

```
DHQH  = -0.0923221 + 43.22535*      X3 + 0.592151*X5
        +H6HC* (X5* (-0.001510957 - 0.5277863E-5*X5*X5)
        + 0.0007545455*SQRT(X5) - 0.03290446*X3)
        + P6HC**0.2* (3.101606*X3 - 0.3019954*SQRT (X3))
DHQHA = DHQH*(fuel heating value/18550.)*reheat efficiency
```

Pressure change equation due to heat addition:

```
DPQP  = 0.00845444 - 0.0415271*FAR7 + XM6* (-0.0917223*SQRT (X5)
        - 0.000150274*X5**3 + XM6* (0.129512*X5 + 0.8015385*DHQHA))
P7HC  = P6HC* (1.0-DPQP)
```

TABLE 8
AFTERBURNER CALCULATION ACCURACY RESULTS

	Average Deviation - %					Maximum Deviation - %				
Engine	1	2	3	4	All	1	2	3	4	All
FN	0.32	0.32	0.31	0.30	0.31	1.65	1.51	1.43	1.59	1.65
WF	0.01	0	0	0	0	0.59	0.30	0	0	0.59
SFC	0.32	0.32	0.31	0.30	0.31	1.41	1.40	1.45	1.61	1.61
PASS	0	0	0	0	0	0	0	0	0	0

With the changes in program size and CPU time mentioned previously, the total cost units were reduced 6.4 percent by this alternate procedure, as shown by the Cost Units equation.

Total CU's = 23.77 + 98.77 x (1.0 + 0.5 x 166,496/171,072)
= <u>170.60</u> CU's

This alternate method consists of a fully generalized temperature rise calculation, but the pressure loss regression equation is considered a more limited application procedure. This regression approach to Rayleigh line conservation of momentum calculation warrants further development to make it more general. The equation of Table 7 may produce higher errors in situations beyond the sample data ranges of Figure 3.

SECTION VII

FIFTH STUDY--COMPRESSOR MAP

The only other major table interpolation in the baseline program which had not been studied is used to obtain compressor characteristics required in the calculation of compressor performance. Compressor tables consist of flow and efficiency as functions of corrected rotor speed and beta where beta is defined by an equation from which pressure ratio is computed (see Figure 4 and Appendix D). To tabulate the map, a family of beta lines are placed on the map based on a second-order equation. The beta equation is formulated for each compressor map such that pressure ratio is a function of beta and flow. The line for beta equal to 1.0 passes through the aerodynamic design point (100% speed and design pressure ratio) and runs down the backbone of the map. The compressor characteristics in the baseline program represent a variable geometry compressor but are not layered maps since the geometry is scheduled versus rotor speed and the map represents that built-in schedule. Therefore, savings resulting from this alternate procedure might be increased in cycles requiring layered compressor maps to represent variable geometry.

As a result of the turbine map study, an alternate format, such as $\Delta H/\theta$, for compressor characteristics was not investigated. The emphasis was placed on evaluating two approaches to curve fitting the existing compressor flow and efficiency tables.

STUDY PLAN

Program area affected: Compressor calculations.

Goal: To replace tabular compressor characteristics with regression models.

Approach: Two methods were investigated. The first was to curve fit each table with a single equation. The second was to curve fit the 1.0 beta line for reference and then generate equations for changes in flow and efficiency on either side of the reference line. It was important to have the regression model cover the same map areas as did the tables, but accuracy in the outlying map regions was not considered as important as the central backbone area where engine operation is more likely to occur.

Step 1: Develop the full map regression equation model.

Step 2: Develop the regionalized regression equation model.

Step 3: Check out each in the baseline parametric deck.

Step 4: Select the better method and perform a full evaluation.

DISCUSSION OF EFFORT

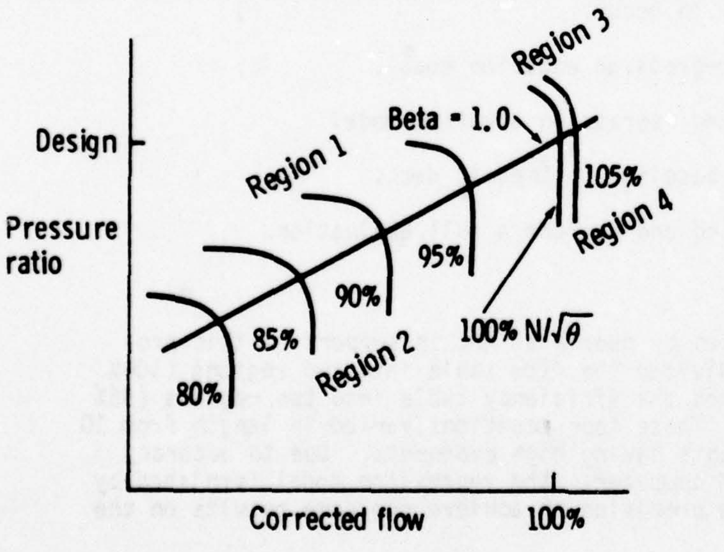
The first approach was undertaken by people at APL in support of this project. Their regression model divided the flow table into two regions (100% speed line being the divider) and the efficiency table into two regions (95% speed line being the divider). These four equations varied in length from 10 to 14 terms with some coefficients having high exponents. Due to accuracy differences between CDC and IBM computers, the regression model furnished by APL had to be changed to double precision to achieve the same results on the IBM computer.

Preliminary evaluation of the APL version of a compressor characteristics regression model showed a slight reduction in program size due to replacing tables with equations. Compute time was reduced 3.3 percent which would be greater on a CDC computer where the double precision would not be necessary. Average deviations in net thrust and fuel flow rate were 0.12 and 0.28 percent with maximums of 1.88 and 4.83 percent respectively. The very low average deviations indicate that high deviations only occur in a few isolated areas and, therefore, this regression model was considered adequate.

The second method involved dividing the compressor map into four regions with the 1.0 beta line and the 100% speed line as the dividers as illustrated in Figure 4. This effort was undertaken at DDA.

This method of compressor map regression was found to be time consuming and to require extra logic, compared to the first method. The final model tested for this regionalized approach achieved the desired results for accuracy and compute time. Figure 5 shows the equations required for this method. The blending at the speed and beta boundaries was added to eliminate the possibility of discontinuities in those regions. The method used was a simple one. Along the 1.0 beta line, a multiplier was added to the delta flow and delta efficiency equations when beta was between 0.99 and 1.01 such that at 0.99 and 1.01 the multiplier was 1.0 and zero at beta equal to 1.0. To blend along the 100% speed line, a weighted average of the two adjacent region equations was used to force continuity.

$$\boxed{\text{Beta} = \left(\frac{Wa}{Wa_{design}}\right)^{\text{Cons 1}} - \frac{R_c - \text{Cons 2}}{R_{c_{design}} - \text{Cons 2}} + 1.0}$$



Equations for beta = 1.0

$\left.\begin{array}{l} Wa = f(N) \\ \eta_c = f(N) \end{array}\right\}$ $N \leq 100\%$

$\left.\begin{array}{l} Wa = f(N) \\ \eta_c = f(N) \end{array}\right\}$ $N > 100\%$

Region equations

$\Delta Wa = f(N, \text{Beta})$

$\Delta \eta_c = f(N, \text{Beta})$

Blending equations

$99.5 < N < 100.5$

$0.99 < \text{Beta} < 1.01$

TE-5060A

Figure 4. Regionalized compressor map regression.

FINAL EVALUATION

The selection of one method over the other was not a clear and concise choice. Accuracy and compute time were comparable except for the maximum fuel flow deviation. The speed of the longer equations and less logic of the first method was approximately equal to that of the shorter equations and complex logic of the second method.

There are other factors to also consider when curve-fitting a compressor map. The APL method requires less alterations to the map since the DDA method involves curve fits of delta flow and efficiency relative to a reference line. There are also more equations to regress in the DDA method and, in some instances, more complex variables were used. However, the DDA method must be considered more flexible in dealing with more irregular compressor characteristics resulting from variable geometry scheduling, surge bleed systems and the like. Thus, the DDA method was selected to represent the fifth alternate procedure in the final deck recognizing the fact the APL method should be selected when reduced manpower or calendar time become major factors or when the compressor map can be regressed with relatively short equations under the APL method.

Table 9 shows the final accuracy results of the regionalized compressor map regression model.

TABLE 9
COMPRESSOR MAP REGRESSION ACCURACY

Engine	Average Deviation - %					Maximum Deviation - %				
	1	2	3	4	All	1	2	3	4	All
FN	0.17	0.18	0.09	0.11	0.14	1.66	1.27	0.50	0.83	1.66
WF	0.21	0.22	0.15	0.14	0.18	1.71	1.43	0.66	0.61	1.71
SFC	0.11	0.10	0.10	0.11	0.11	1.24	0.83	0.59	0.67	1.24
PASS	+2.2	+8.3	+0.2	+4.5	+3.8	300	200	150	200	300

The 3.1 percent reduction in CPU time and a slight increase in program size resulted in a cost savings of only 2.7 percent as shown by the Cost Unit equation.

$$\text{Total CU's} = 23.77 + 102.35 \times (1.0 + 0.5 \times 171{,}248/171{,}072)$$
$$= \underline{177.35} \text{ CU's}$$

Appendix D contains a listing of the final compressor map regression model.

SECTION VIII

SIXTH STUDY--COMPRESSION PROCESS

The topic selected for the final study was thermal process regression. This concept involves replacing the use of thermodynamic state properties for ideal compression and expansion processes with regression equations of the ideal enthalpy change of the process as derived from the thermo properties. This regression equation application would eliminate the use of the relative pressure function by incorporating its effect into the process regression model. The net effect is the reduction of time in computing component performance.

Based on that concept, the sixth alternate procedure was established as changing the compressor ideal enthalpy rise calculation to a regression equation. Its evaluation will indicate the potential of applying this approach to other areas of the program, primarily the turbine expansion process.

STUDY PLAN

Program area affected: Compressor ideal enthalpy rise calculation.

Goal: To replace the use of thermo properties with a regression equation.

Step 1: Generate a data base using the calculations and thermo properties of the baseline program. Select ranges of the independent variables of compressor inlet temperature and pressure ratio to adequately cover the parametric deck application.

Step 2: Curve fit the ideal enthalpy rise data.

Step 3: Curve fit the ideal exit enthalpy data.

Step 4: Incorporate the more accurate equation into the compressor calculations and execute check runs.

Step 5: Perform full evaluation.

DISCUSSION OF EFFORT

A data base for regression analysis was generated using the calculations of the baseline program to compute compressor exit ideal enthalpy as a function of compressor inlet temperature and compressor pressure ratio. The compressor equations and the equations of the thermodynamic properties were studied to select the terms to be entered into the regression analysis.

A study of the baseline parametric deck established the required range of compressor inlet temperature to be -110 to 620°F. The range of compressor pressure ratio was 2.5 to 20.0. Therefore, the sample data was generated to extend slightly beyond those ranges and both ideal exit enthalpy and ideal enthalpy rise were made available for regression analysis.

The regression analysis showed ideal enthalpy rise (ΔH) to be slightly better to curve fit than the ideal exit enthalpy. The natural logarithm of pressure ratio was obviously an essential term. A study of the thermo properties equations developed in the first alternate procedure showed that compressor inlet enthalpy raised to low fractional exponents (like 0.1 to 0.4) should also be important.

With this information and a data sample, the regression analysis rapidly provided an acceptable equation for ideal enthalpy rise. Table 10 shows the equation incorporated into the compressor calculations. Figure 5 is an error analysis map of that equation showing its accuracy in the curve fit ranges of independent variables and how those errors increase in the extrapolated regions.

TABLE 10
COMPRESSION PROCESS REGRESSION EQUATION

$$\Delta H = 174.7182 - 1.211559*H1 - 117.7741 * X11 - 0.002270764 * X16 + 0.8531293E\text{-}6*X18 - 8.4886594 * X19 - 0.1294983E\text{-}5 * X22 + 0.072892 * X24 + 4.219596 * X27 + 0.1069751E\text{-}4*X29$$

where:
- RC = Compressor pressure ratio
- H = Compressor ideal enthalpy rise
- H1 = Compressor inlet enthalpy
- X11 = H1 ** 0.1
- X12 = X11 * X11
- X13 = X12 * X11
- X14 = X13 * X11
- RCLN = ALOG (RC)
- X16 = (RCLN + X11) ** 6
- X18 = (RCLN + X11) ** 10
- X19 = (RCLN + X12) ** 2
- X22 = (RCLN + X12) ** 8
- X24 = (RCLN + X13) ** 4
- X27 = (RCLN + X14) ** 2
- X29 = (RCLN + X14) ** 6

FINAL EVALUATION

The full evaluation was performed on the developed equation. Table 11 shows the average deviations to be very low even though the maximum deviation in net thrust did exceed two percent on one data point (36,089 ft, 0.95 Mn, max power). The slight reduction in PASS indicates that the equation provides somewhat smoother results than the thermo properties of the baseline program which contains iteration tolerances on certain properties. That advantage will be lessened in the combined analysis due to using the new thermo properties routine which has no iterations.

TABLE 11
COMPRESSION PROCESS REGRESSION ACCURACY

	Average Deviation - %					Maximum Deviation - %				
Engine	1	2	3	4	All	1	2	3	4	All
FN	0.11	0.22	0.20	0.16	0.17	0.69	2.13	0.66	0.57	2.13
WF	0.12	0.15	0.15	0.12	0.14	0.63	0.64	0.76	0.71	0.76
SFC	0.09	0.13	0.13	0.12	0.12	0.37	2.17	0.50	0.48	2.17
PASS	-4.7	-3.1	-5.9	-5.2	-4.7	100	100	-67	-53.6	100

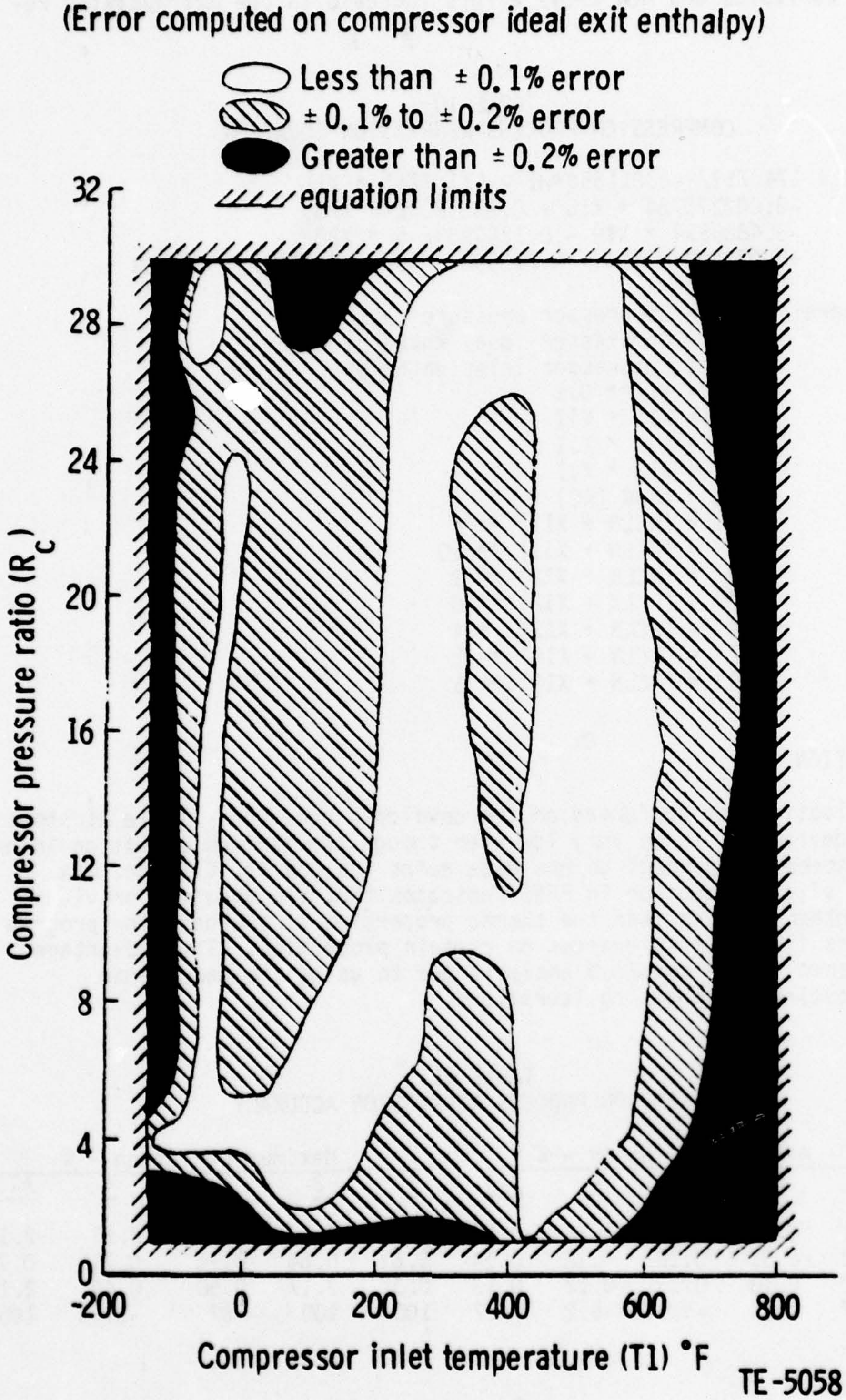


Figure 5. Compression Process Regression Equation Error Map.

The CPU time was reduced 4.3 percent and the program size increased slightly to give a cost reduction of 3.7 percent. This is shown by the following Cost Unit equation.

$$\text{Total CU's} = 23.77 + 101.13 \times (1.0 + 0.5 \times 171{,}344/171{,}072)$$
$$= \underline{175.55}\ \text{CU's}$$

This alternate procedure indicates that there is potential for thermal process regression throughout the parametric deck. Further studies of the compression process regression might shorten the equation used and slightly improve on the cost reduction in other applications. One example is where a fan is involved rather than a high pressure compressor. In that case, the range of pressure ratio is much less and the equation could be simplified.

SECTION IX

FINAL COMBINED PROCEDURES

The final evaluation involved combining all six alternate procedures into the same parametric deck. All six were selected since all satisfied the requirements of showing a cost reduction with acceptable average deviations in engine performance even though some maximum deviations did extend slightly beyond desired levels. The primary purpose of the combined evaluation was to determine the interaction between the various alternate procedures. It was necessary to show whether or not any of the new procedures compounded the deviations of other procedures.

The combining of the six procedures was relatively simple since each dealt with separate areas of the program except for the last two dealing with the compressor. The program size changed as expected and checkout was done after each alternate procedure was added to a separate copy of the baseline parametric deck.

FINAL EVALUATION

The full evaluation was made on this final program. Average deviations in engine performance increased only slightly more than in the turbine map regression study. Table 12 shows the maximum deviation in net thrust to be 2.82 percent, which is 0.75 percent higher than in any individual procedure evaluation. This deviation was studied further and is discussed later in this section. The reduction in PASS of 24.6 percent which probably accounts for half of the CPU time reduction and indicates the compatibility of the alternate procedures in working smoothly together.

TABLE 12
FINAL COMBINES PROCEDURES ACCURACY DATA.

	Average Deviation - %					Maximum Deviation - %				
Engine	1	2	3	4	All	1	2	3	4	All
FN	0.70	0.69	0.64	0.67	0.68	1.85	2.82	2.28	2.59	2.82
WF	0.69	0.61	0.55	0.60	0.61	2.33	1.99	1.62	1.59	2.33
SFC	0.72	0.68	0.69	0.63	0.68	2.02	2.45	2.27	1.92	2.45
PASS	-27.8	-15.6	-28.1	-26.7	-24.6	100	200	100	100	200

The program size was reduced 14,832 bytes, or 8.7 percent. Compute time was reduced 52.0 percent for a final cost reduction of 46.4 percent using the RSTEP Cost Unit equation.

$$\text{Total CU's} = 23.77 + 50.75 \times (1.0 + 0.5 \times 156{,}240/171{,}072)$$
$$= \underline{97.69}\ \text{CU's}$$

Further Accuracy Study

It was determined that further error analysis would aid in showing the usefulness of the combined procedures. Thus, Figure 6 was made to illustrate the error distribution in net thrust and fuel flow rate for the 740-point full

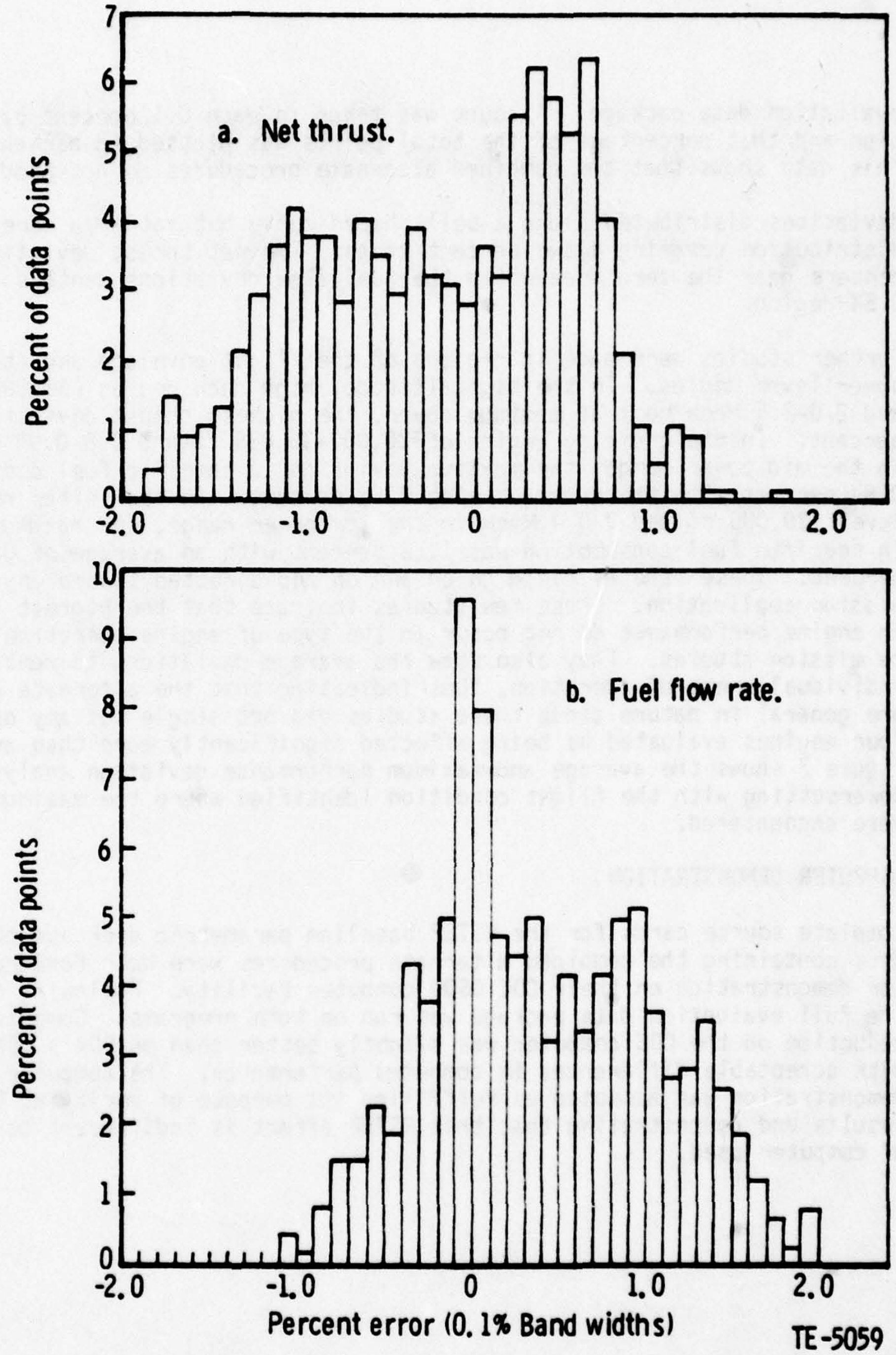


Figure 6. Final Program Error Distribution.

evaluation data package. A count was taken in each 0.1 percent band of deviation and that percentage of the total points was plotted in bar-chart form. This data shows that the combined alternate procedures do not produce

deviations distributed along a bell-shaped curve but rather a more uniform distribution covering a two percent range. The net thrust deviation range centers near the zero area while the fuel flow deviations centers nearer the 0.5% region.

Further studies were made in regions of the flight envelope and at certain power lever angles. In the high altitude, high Mach region (36,089-70,000 ft and 2.0-2.5 Mach no.) at maximum power, the highest thrust deviation was 1.8 percent. In the cruising region of 20,000-36,089 ft and 0.8-0.95 Mach number in the mid power range, the maximum deviation in specific fuel consumption was 0.94 percent with the average being 0.55 percent. In the loiter region of sea level -20,000 ft and 0-0.4 Mach in the low power range, the maximum deviation in specific fuel consumption was 1.18 percent with an average of 0.57 percent. These studies could go on and on and directed toward any given mission application. These few studies indicate that the highest deviations in engine performance do not occur in the type of engine operation most common to mission studies. They also show the average deviations to remain low for individual areas of operation, thus indicating that the alternate procedures are general in nature since these studies did not single out any one of the four engines evaluated as being affected significantly more than another. Figure 7 shows the average and maximum performance deviation analysis versus powersetting with the flight condition identified where the maximum errors were encountered.

COMPUTER DEMONSTRATION

Complete source cards for the RSTEP baseline parametric deck and the final deck containing the combined alternate procedures were both forwarded to APL for demonstration on their CDC 6600 computer facility. Following checkout, the full evaluation data package was run on both programs. Compute time reduction on the CDC computer was slightly better than on DDA's IBM computer with acceptable differences in computed performance. The computer demonstration was accepted as fulfilling its purpose of verifying DDA's results and demonstrating that this RSTEP effort is indifferent to the brand of computer used.

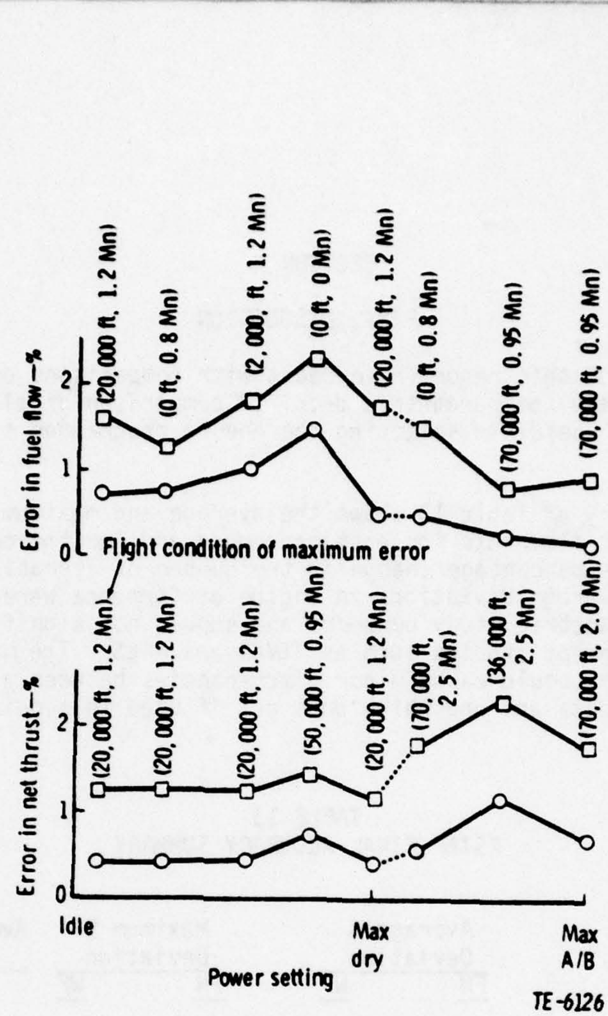


Figure 7. Final Program Error Analysis.

SECTION X

FINAL DISCUSSION

Previous sections of this report have dealt with comparisons of each alternate procedure to the baseline parametric deck. A comparison of all alternate procedures at once is useful in selecting the ones a programmer might implement first.

The accuracy summary of Table 13 shows the average and maximum deviations in net thrust and fuel flow rate for each procedure and for the combined procedures. The average percentage change in the number of iteration passes is also shown. The average deviations in engine performance were considered acceptable for parametric study purposes and should not significantly affect the accuracy of concept studies such as TEVCS ans ARES. The maximum deviations, however, could cause minor discrepancies between a parametric deck having these shortcuts and one which does not if used in a point-by-point comparison.

TABLE 13
RSTEP FINAL ACCURACY SUMMARY

	Average % Deviation		Maximum % Deviation		Average % Reduction In Loop Counter
	FN	WF	FN	WF	PASS
Thermo properties	0.08	0.09	0.46	0.53	5.2
Matrix coefficients	0.05	0.05	0.35	0.27	20.0
Turbine maps	0.42	0.62	1.25	2.38	(-6.9)
Reheat calculations	0.31	0.00	1.65	0.59	0.0
Compressor map	0.14	0.18	1.66	1.71	(-3.8)
Compression process	0.17	0.14	2.13	0.76	4.7
Final program	0.64	0.61	2.30	2.33	24.6

The results of the PPE Analyzer were not shown in each individual section. The CPU time breakdown is shown in Table 14 for comparison purposes. This data is the result of a statistical analysis and is, by no means, perfect. Some minor deviations are only due to statistical sampling error--generally less than one to two percent. However, the data does reinforce the basic conclusions of the project.

The compute time breakdown within the program illustrates several points.

1) As overall compute time is reduced, the percentage of time increases for unchanged areas of the program such as bookkeeping routines and system I/O effort.
2) The percentage time spent in table look-up routines was reduced by 67 percent due to regression models.
3) The price paid for reduction in table look-up was a substantial increase in mathematical functions such as logarithms and exponentials, and increases in the routines containing the equations.

4) The final program requires nearly the same amount of thermo properties to be generated as did the baseline program - the only elimination of those properties being in the compressor routine for ideal enthalpy rise. The new thermo properties routine (Appendix A) produces nearly the same quantity of data but requires only 14.3 percent of the total CPU time versus 25.9 percent for the baseline version, thus reducing the time spent in this routine by 45 percent. This alternate procedure must be considered well worth the effort required to change routines, not only in parametric decks but also in all other engine models.

TABLE 14
CPU TIME BREAKDOWN

Program Segment	Base	AP 1	AP 2	AP 3	AP 4	AP 5	AP 6	Final
	Percent CPU Time Used By Each Program Segment							
Bookkeeping Routines	1.56	2.12	1.68	1.69	1.49	1.71	1.84	2.87
Compressor	2.46	3.03	1.96	2.79	2.58	3.36	2.74	4.93
Primary burner	0.48	0.52	0.36	0.51	0.44	0.39	0.46	0.46
Turbine	1.00	0.92	0.72	2.62	0.93	0.74	0.93	3.31
Afterburner	0.46	0.55	0.60	0.52	0.75	0.51	0.49	1.29
Exhaust nozzle	1.01	1.24	1.07	1.20	1.29	1.02	1.24	1.43
Misc cycle calc	6.22	7.16	5.93	6.76	6.65	6.64	6.10	8.80
Iteration Routines	3.74	3.70	4.21	4.00	3.30	3.53	3.59	6.32
Thermo Properties	25.92	13.48	25.49	30.76	27.77	27.25	24.58	14.32
Table Interpolations	32.12	36.51	31.83	17.62	28.94	28.39	33.96	10.61
Math Functions	15.74	19.63	14.97	20.50	16.26	16.61	15.50	28.90
I/O & system misc	9.29	11.14	11.18	11.03	9.60	9.85	8.57	16.76

SECTION XI

CONCLUSIONS

The conclusion of this study is that substantial cost savings are possible through diligent efforts to reduce computing time. Efforts toward program size reduction are less rewarding. Other general conclusions are:

- Developed procedures do not need to change the engine simulation philosophy of maintaining component identity and cycle matching.
- A few of the alternate procedures can be applied to other forms of engine simulations used in the industry. The effort of developing some alternate procedures is required only once and can be applied to all parametric decks while others require new effort on each program.
- Regression modeling of tabular data and of calculation results arrived at through iteration tends to smooth the cycle matching process into converging in fewer passes.
- These improved procedures will normally be independent of the brand of computer being used. However, different computer charging algorithms will impact the magnitude of savings.

Six specific alternate procedures were evaluated. These were selected based on having high applicability in the industry. The following conclusions were drawn about the future use of these alternate procedure in parametric engine computer simulations.

- Thermodynamic properties are used throughout the programs. Reductions in the polynomial order used provides a substantial reduction in cost and can be done with little effect in engine performance. This effort should also be directly applicable to other forms of engine models besides parametric decks.
- Any method which significantly reduces the number of iteration passes is very beneficial. Matrix coefficient prediction is relatively simple to do in customer decks of all kinds and is very rewarding in cost reduction. It does not affect engine performance significantly and coefficients are generally well-behaved functions.
- Turbine map regression can be cost effective but may not be desirable in some situations. It must be done once for each turbine map. In this project it was worthwhile because of the size and complexity of the tables.
- The use of thermodynamic properties and combustion equations for afterburner temperature rise is significantly better than the use of temperature rise and adjustment tables. The use of regression equations for pressure loss due to heat addition (Fanno and Rayleigh lines for conservation of energy and momentum) is considerably faster than a momentum balance iteration used in the baseline program. These changes apply to all engine simulations which include reheat calculations.
- Compressor map regression did not appear to be very cost effective in this project. This probably should only be considered for much larger compressor map tabulations or for a very high usage parametric deck.
- Compression process regression did not show a high savings. However, it is considered worthwhile due to the low effort level required and its wide application in all forms of engine models.
- The combination of all six alternate procedures did not greatly increase the average and maximum deviations in engine performance above those produced by the worst single alternate procedure. This tends to indicate that new alternate procedures can be developed and integrated into parametric decks without concern for their effects on engine performance being additive.

SECTION XII

RECOMMENDATIONS

Recommendations are clear for some of the alternate procedures developed in this project. The benefits and applicability of others become more dependent on parametric deck programming time available and on expected amount of program usage.

Table 15 shows a qualitative estimate of manpower and calendar time required to implement each of the six procedures studied. These figures are simply derived from judgement and the experience of this project and are shown as ratios using the thermo properties as the reference base procedure. It is assumed that the detailed discussion sections of this report would aid in the development and implementation of each procedure.

TABLE 15
ESTIMATED DEVELOPMENT EFFORT

Procedure	Relative Manpower	Relative Time	Application
Thermo Properties	1.0*	1.0*	One-time effort, broad usage
Matrix Coefficients	0.5	0.5	Once per program
Turbine Maps	3.0	2.0	Once per turbine map
Reheat Calculations	1.5	1.0	One-time effort, broad application
Compressor Map	2.0	1.0	Once per compressor map
Compression Process	0.3	0.2	Once per range desired, broad application

*Note--all figures related as ratios of thermo properties effort.

All factors considered, the alternate procedures considered essential are: thermo properties, matrix coefficients and reheat calculations. Second in order of priority and on a probably-should-use basis are: turbine map regression and thermal process regression. That leaves compressor map regression as being recommended only when time permits or when compressor maps become very large and awkward in table form.

APPENDIX A

NEW THERMAL PROPERTIES ROUTINE

```
      FUNCTION GASP (XARG,FAIN,KMN)
C     MULTI-PURPOSE GAS PROPERTIES FUNCTION SUBPROGRAM
C
C     KMN  FUNCTION     PURPOSE
C      0     FZAST      XARG=0.0 RETURNS STOICH. FUEL-AIR RATIO OF JP-4
C      1     TTOH       TEMPERATURE, FUEL-AIR RATIO RETURN ENTHALPY
C      2     HTOT       ENTHALPY, FUEL-AIR RATIO RETURN TEMPERATURE (R)
C      3     TTOPHI     TEMPERATURE, FUEL-AIR RATIO RETURN PHI (LN PR)
C      4     PHITOH     PHI (LN PR), FUEL-AIR RATIO RETURN ENTHALPY
C      5     TTOGAM     TEMPERATURE, FUEL-AIR RATIO RETURN GAMMA (CP/CV)
C      6     HTOPHI     ENTHALPY, FUEL-AIR RATIO RETURN PHI (LN PR)
C      7     TTOHL      TEMPERATURE RETURNS FUEL H-LAMBDA (BTU/LB)
C      8     FTOR       FUEL-AIR RATIO RETURNS GAS CONSTANT R (FT-LB/LB R)
C      9     TTOCP      TEMPERATURE,FUEL-AIR RATIO RETURN CP (BTU/LB R)
C     10     TTOHF      FUEL TEMPERATURE RETURNS FUEL ENTHALPY (BTU/LB)
C
C        ** NOTE **  DELTA PHI = R / 778.0 * ALOG (PRESSURE RATIO)
C
      DIMENSION C(224),C1(32),C2(32),C3(32),C4(32),C5(32),C6(32),
     1 C7(32),XMIN(5),XB1(5),XB2(5),XB3(5),XMAX(5)
      EQUIVALENCE (C(1),C1(1)),(C(33),C2(1)),(C(65),C3(1)),
     1 (C(97),C4(1)),(C(129),C5(1)),(C(161),C6(1)),(C(193),C7(1))
      DATA RAIR/53.3471/,RST/53.4577/,FZAST/0.067751/
      DATA XMIN/300.0,71.61,73.24,1.462,1.457/
      DATA XB1/800.,191.813,200.212,1.69561,1.70303/
      DATA XB2/1550.,382.427,408.309,1.86292,1.88548/
      DATA XB3/2750.,717.844,782.551,2.02248,2.06338/
      DATA XMAX/4500.0,1240.,1376.,2.17,2.23/
C        C(1-16)=T-H(AIR)                  C(17-32)=T-H(ST)
      DATA C1/
     *-0.71390728E+00, 0.24325137E+00,-0.98793134E-05, 0.83002278E-08,
     * 0.52243748E+01, 0.22439916E+00, 0.97868733E-05, 0.15758597E-08,
     * 0.15097341E+02, 0.20207592E+00, 0.26498997E-04,-0.25657457E-08,
     *-0.22339584E+02, 0.24332677E+00, 0.11175025E-04,-0.64792716E-09,
     * 0.78070774E+00, 0.23723099E+00, 0.14039702E-04, 0.12907762E-08,
     * 0.34812880E+01, 0.23007784E+00, 0.19505570E-04, 0.36067200E-09,
     * 0.12971856E+02, 0.20980115E+00, 0.34007018E-04,-0.31038473E-08,
     *-0.29986081E+02, 0.25592025E+00, 0.17306630E-04,-0.10637762E-08/
C        C(33-48)=H(AIR)-T                 C(49-64)=H(ST)-T
      DATA C2/
     * 0.27831925E+01, 0.41149368E+01, 0.67876186E-03,-0.24172994E-05,
     *-0.24598838E+02, 0.44861265E+01,-0.98760121E-03, 0.61326477E-07,
     *-0.23972732E+02, 0.45496253E+01,-0.13394461E-02, 0.53598519E-06,
     * 0.12057719E+03, 0.39294664E+01,-0.44119554E-03, 0.97383046E-07,
     *-0.33287904E+01, 0.42180836E+01,-0.10650836E-02, 0.18844425E-06,
     *-0.12830747E+02, 0.43219603E+01,-0.14037676E-02, 0.47262769E-06,
     * 0.60832972E+01, 0.42283757E+01,-0.12831391E-02, 0.46067891E-06,
     * 0.16791743E+03, 0.36011718E+01,-0.46134034E-03, 0.97021437E-07/
C           C(65-72)=T**.1-PHI(AIR)         C(81-84)=T**.1-PHI(ST)
C           C(73-80)=T-PHI(AIR)             C(85-96)=T-PHI(ST)
      DATA C3/
     *-0.75087058E+01, 0.11475318E+02,-0.51497230E+01, 0.86417789E+00,
     *-0.46468825E+01, 0.72950252E+01,-0.31163430E+01, 0.53481679E+00,
     * 0.14782989E+01, 0.34316823E-03,-0.72263217E-07, 0.70674258E-11,
     * 0.15811699E+01, 0.22969926E-03,-0.30136563E-07, 0.18063403E-11,
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     *-0.52941924E+01, 0.81270549E+01,-0.35060003E+01, 0.60411050E+00,
     * 0.13281128E+01, 0.64609301E-03,-0.26113412E-06, 0.49219422E-10,
     * 0.14672766E+01, 0.36966348E-03,-0.75831945E-07, 0.73580599E-11,
     * 0.15730452E+01, 0.25260709E-03,-0.32232190E-07, 0.18963450E-11/
C       C(97-112)=PHI(AIR)-H(AIR)**.1 C(113-128)=PHI(ST)-H(ST)**.1
      DATA C4/
     * 0.12866474E+01,-0.50431069E+00, 0.60198901E+00,-0.96568664E-01,
     * 0.12687452E+01,-0.48461587E+00, 0.59568625E+00,-0.96029524E-01,
     * 0.91777572E+00, 0.19520990E-01, 0.35762422E+00,-0.59218624E-01,
     *-0.18693399E-01, 0.13873334E+01,-0.30853608E+00, 0.48964155E-01,
     * 0.13874365E+01,-0.70862184E+00, 0.75642727E+00,-0.13680069E+00,
     * 0.11643026E+01,-0.31662774E+00, 0.52539830E+00,-0.91123937E-01,
     * 0.78653828E+00, 0.24059154E+00, 0.25300707E+00,-0.47039022E-01,
     *-0.12401104E+00, 0.15471735E+01,-0.37218696E+00, 0.52718435E-01/
C       C(129-144)=T-CP(AIR)          C(145-160)=T-CP(ST)
      DATA C5/
     * 0.24206170E+00,-0.13498446E-04, 0.14163915E-07, 0.60081127E-11,
     * 0.25105719E+00,-0.52204204E-04, 0.67739345E-07,-0.18052740E-10,
     * 0.17938349E+00, 0.86932045E-04,-0.24281504E-07, 0.26495125E-11,
     * 0.22299184E+00, 0.39327934E-04,-0.66199578E-08, 0.42502020E-12,
     * 0.23700038E+00, 0.29777156E-04, 0.13666939E-09, 0.25430268E-11,
     * 0.24893908E+00,-0.11727146E-04, 0.45595422E-07,-0.12747725E-10,
     * 0.18947177E+00, 0.98822305E-04,-0.24538500E-07, 0.24548297E-11,
     * 0.21705646E+00, 0.67578018E-04,-0.12417787E-07, 0.85238710E-12/
C       C(161-176)=H(AIR)**.1-PHI(AIR)C(177-192)=H(ST)**.1-PHI(ST)
      DATA C6/
     *-0.48747106E+01, 0.82931926E+01,-0.37562603E+01, 0.67972526E+00,
     *-0.48883198E+01, 0.82628565E+01,-0.37036996E+01, 0.66206651E+00,
     *-0.20136861E+01, 0.35768012E+01,-0.11567870E+01, 0.20052726E+00,
     * 0.69769981E+00,-0.58838445E+00, 0.97647125E+00,-0.16374179E+00,
     *-0.54065754E+01, 0.93065379E+01,-0.44349213E+01, 0.83598165E+00,
     *-0.46600228E+01, 0.78951606E+01,-0.35473030E+01, 0.65026365E+00,
     *-0.19411139E+01, 0.34762933E+01,-0.11527495E+01, 0.21761018E+00,
     * 0.14941066E+01,-0.17630590E+01, 0.15114258E+01,-0.23405149E+00/
C       C(193-208)=T-HL               C(209-224)=T-HF
      DATA C7/
     * 0.22841121E+02, 0.14837061E+00, 0.36708269E-03,-0.10216824E-06,
     *-0.25633651E+02, 0.32317041E+00, 0.15480752E-03,-0.15271672E-07,
     *-0.18400146E+02, 0.32382499E+00, 0.14482488E-03,-0.11046188E-07,
     *-0.14284785E+03, 0.44179913E+00, 0.10780869E-03,-0.72016790E-08,
     * 0.22841121E+02, 0.14837061E+00, 0.36708269E-03,-0.10216824E-06,
     *-0.25633651E+02, 0.32317041E+00, 0.15480752E-03,-0.15271672E-07,
     *-0.18400146E+02, 0.32382499E+00, 0.14482488E-03,-0.11046188E-07,
     *-0.14284785E+03, 0.44179913E+00, 0.10780869E-03,-0.72016790E-08/
      IF (KMN.GT.0) GO TO 790
      GASP=FZAST
      GO TO 1430
  790 FA=FAIN
      IF (FA.LT.-0.001 .OR. FA.GT.FZAST+0.001) GO TO 880
      X=XARG
      FACT=0.0
      IF (FA.NE.0.0) FACT=FA*(1.0+FZAST)/(FZAST*(1.0+FA))
      GO TO (930,1440,1150,1480,1560,1700,1950,1670,1560,1970),KMN
C       ANY TYPE OF FAILURE CAUSES AN ANSWER OF 0.0 TO BE RETURNED
  880 GASP=0.0
      GO TO 1430
```

```
  930 IF (X.LT.XMIN(1)) GO TO 880
      IF (X.GT.XB2(1)) GO TO 990
      IF (X.GT.XB1(1)) GO TO 970
C           CURVE FROM TEMPERATURE TO AIR ENTHALPY - LOW RANGE
      XAIR=C(1)+X*(C(2)+X*(C(3)+X*C(4)))
      GO TO 1030
C           CURVE FROM TEMPERATURE TO AIR ENTHALPY - MID LOW RANGE
  970 XAIR=C(5)+X*(C(6)+X*(C(7)+X*C(8)))
      GO TO 1030
  990 IF (X.GT.XB3(1)) GO TO 1020
C           CURVE FROM TEMPERATURE TO AIR ENTHALPY - MID HIGH RANGE
      XAIR=C(9)+X*(C(10)+X*(C(11)+X*C(12)))
      GO TO 1030
C           CURVE FROM TEMPERATURE TO AIR ENTHALPY - HIGH RANGE
 1020 IF (X.GT.XMAX(1)) GO TO 880
      XAIR=C(13)+X*(C(14)+X*(C(15)+X*C(16)))
 1030 IF (FA.EQ.0.0) GO TO 1390
      IF (X.GT.XB2(1)) GO TO 1080
      IF (X.GT.XB1(1)) GO TO 1060
C           CURVE FROM TEMPERATURE TO PRODUCTS ENTHALPY - LOW RANGE
      XST=C(17)+X*(C(18)+X*(C(19)+X*C(20)))
      GO TO 1370
C           CURVE FROM TEMPERATURE TO PRODUCTS ENTHALPY - MID LOW RANGE
 1060 XST=C(21)+X*(C(22)+X*(C(23)+X*C(24)))
      GO TO 1370
 1080 IF (X.GT.XB3(1)) GO TO 1130
C           CURVE FROM TEMPERATURE TO PRODUCTS ENTHALPY - MID HIGH RANGE
      XST=C(25)+X*(C(26)+X*(C(27)+X*C(28)))
      GO TO 1370
C           CURVE FROM TEMPERATURE TO PRODUCTS ENTHALPY - HIGH RANGE
 1130 XST=C(29)+X*(C(30)+X*(C(31)+X*C(32)))
      GO TO 1370
 1150 IF (X.LT.XMIN(1)) GO TO 880
      IF (X.GT.XB2(1)) GO TO 1180
      IF (X.GT.XB1(1)) GO TO 1170
C           CURVE FROM TEMPERATURE**.1 TO AIR PHI - LOW RANGE
      XT=X**.1
      XAIR=C(65)+XT*(C(66)+XT*(C(67)+XT*C(68)))
      GO TO 1250
C           CURVE FROM TEMPERATURE**.1 TO AIR PHI - MID LOW RANGE
 1170 XT=X**.1
      XAIR=C(69)+XT*(C(70)+XT*(C(71)+XT*C(72)))
      GO TO 1250
 1180 IF (X.GT.XB3(1)) GO TO 1190
C           CURVE FROM TEMPERATURE TO AIR PHI - MID HIGH RANGE
      XAIR=C(73)+X*(C(74)+X*(C(75)+X*C(76)))
      GO TO 1250
 1190 IF (X.GT.XMAX(1)) GO TO 880
C           CURVE FROM TEMPERATURE TO AIR PHI - HIGH RANGE
      XAIR=C(77)+X*(C(78)+X*(C(79)+X*C(80)))
 1250 IF (FA.EQ.0.0) GO TO 1390
      IF (X.GT.XB2(1)) GO TO 1300
      IF (X.GT.XB1(1)) GO TO 1280
C           CURVE FROM TEMPERATURE**.1 TO PRODUCTS PHI - LOW RANGE
      XST=C(81)+XT*(C(82)+XT*(C(83)+XT*C(84)))
      GO TO 1370
```

```
C           CURVE FROM TEMPERATURE TO PRODUCTS PHI - MID LOW RANGE
 1280 XST=C(85)+X*(C(86)+X*(C(87)+X*C(88)))
      GO TO 1370
 1300 IF (X.GT.XB3(1)) GO TO 1350
C           CURVE FROM TEMPERATURE TO PRODUCTS PHI - MID HIGH RANGE
      XST=C(89)+X*(C(90)+X*(C(91)+X*C(92)))
      GO TO 1370
C           CURVE FROM TEMPERATURE TO PRODUCTS PHI - HIGH RANGE
 1350 XST=C(93)+X*(C(94)+X*(C(95)+X*C(96)))
C           LINEAR INTERPOLATION BETWEEN AIR AND PRODUCTS EQUATIONS
 1370 GASP=XAIR+(XST-XAIR)*FACT
      GO TO 1430
 1390 GASP=XAIR
 1430 RETURN
 1440 IF (X.LT.XMIN(2)) GO TO 880
      IF (X.GT.XB2(2)) GO TO 1444
      IF (X.GT.XB1(2)) GO TO 1442
C           CURVE FROM AIR ENTHALPY TO TEMPERATURE - LOW RANGE
      XAIR=C(33)+X*(C(34)+X*(C(35)+X*C(36)))
      IF (FA.NE.0.0) CPA=C(129)+XAIR*(C(130)+XAIR*(C(131)+XAIR*C(132)))
      GO TO 1450
C           CURVE FROM AIR ENTHALPY TO TEMPERATURE - MID LOW RANGE
 1442 XAIR=C(37)+X*(C(38)+X*(C(39)+X*C(40)))
      IF (FA.NE.0.0) CPA=C(133)+XAIR*(C(134)+XAIR*(C(135)+XAIR*C(136)))
      GO TO 1450
 1444 IF (X.GT.XB3(2)) GO TO 1446
C           CURVE FROM AIR ENTHALPY TO TEMPERATURE - MID HIGH RANGE
      XAIR=C(41)+X*(C(42)+X*(C(43)+X*C(44)))
      IF (FA.NE.0.0) CPA=C(137)+XAIR*(C(138)+XAIR*(C(139)+XAIR*C(140)))
      GO TO 1450
 1446 IF (X.GT.XMAX(3)) GO TO 880
C           CURVE FROM AIR ENTHALPY TO TEMPERATURE - HIGH RANGE
      XAIR=C(45)+X*(C(46)+X*(C(47)+X*C(48)))
      IF (FA.NE.0.0) CPA=C(141)+XAIR*(C(142)+XAIR*(C(143)+XAIR*C(144)))
 1450 ANS=XAIR
      IF (FA.EQ.0.0) GO TO 1459
      IF (X.GT.XB2(3)) GO TO 1454
      IF (X.GT.XB1(3)) GO TO 1452
C           CURVE FROM PRODUCTS ENTHALPY TO TEMPERATURE - LOW RANGE
      XST=C(49)+X*(C(50)+X*(C(51)+X*C(52)))
      CPS=C(145)+XST*(C(146)+XST*(C(147)+XST*C(148)))
      GO TO 1458
C           CURVE FROM PRODUCTS ENTHALPY TO TEMPERATURE - MID LOW RANGE
 1452 XST=C(53)+X*(C(54)+X*(C(55)+X*C(56)))
      CPS=C(149)+XST*(C(150)+XST*(C(151)+XST*C(152)))
      GO TO 1458
 1454 IF (X.GT.XB3(3)) GO TO 1456
C           CURVE FROM PRODUCTS ENTHALPY TO TEMPERATURE - MID HIGH RANGE
      XST=C(57)+X*(C(58)+X*(C(59)+X*C(60)))
      CPS=C(153)+XST*(C(154)+XST*(C(155)+XST*C(156)))
      GO TO 1458
 1456 IF (X.GT.XMAX(3)) GO TO 880
C           CURVE FROM PRODUCTS ENTHALPY TO TEMPERATURE - HIGH RANGE
      XST=C(61)+X*(C(62)+X*(C(63)+X*C(64)))
      CPS=C(157)+XST*(C(158)+XST*(C(159)+XST*C(160)))
 1458 CP=CPA+(CPS-CPA)*FACT
```

```
      ANS=(CPA*XAIR+(CPS*XST-CPA*XAIR)*FACT)/CP
 1459 IF (KMN.EQ.6) GO TO 1460
      GASP=ANS
      GO TO 1430
 1460 X=ANS
      GO TO 1150
 1480 IF (X.LT.XMIN(4)) GO TO 880
      IF (X.GT.XB2(4)) GO TO 1500
      IF (X.GT.XB1(4)) GO TO 1490
C         CURVE FROM AIR PHI TO AIR ENTHALPY**.1 - LOW RANGE
      XAIR=C(97)+X*(C(98)+X*(C(99)+X*C(100)))
      GO TO 1520
C         CURVE FROM AIR PHI TO AIR ENTHALPY**.1 - MID LOW RANGE
 1490 XAIR=C(101)+X*(C(102)+X*(C(103)+X*C(104)))
      GO TO 1520
 1500 IF (X.GT.XB3(4)) GO TO 1510
C         CURVE FROM AIR PHI TO AIR ENTHALPY**.1 - MID HIGH RANGE
      XAIR=C(105)+X*(C(106)+X*(C(107)+X*C(108)))
      GO TO 1520
 1510 IF (X.GT.XMAX(5)) GO TO 880
C         CURVE FROM AIR PHI TO AIR ENTHALPY**.1 - HIGH RANGE
      XAIR=C(109)+X*(C(110)+X*(C(111)+X*C(112)))
 1520 IF (FA.EQ.0.0) GO TO 1530
      IF (X.GT.XB2(5)) GO TO 1524
      IF (X.GT.XB1(5)) GO TO 1522
C         CURVE FROM PRODUCTS PHI TO PRODUCTS ENTHALPY**.1 - LOW RANGE
      XST=C(113)+X*(C(114)+X*(C(115)+X*C(116)))
      GO TO 1528
C         CURVE FROM PRODUCTS PHI TO PRODUCTS ENTHALPY**.1 - MID LOW RANG
 1522 XST=C(117)+X*(C(118)+X*(C(119)+X*C(120)))
      GO TO 1528
 1524 IF (X.GT.XB3(5)) GO TO 1526
C         CURVE FROM PRODUCTS PHI TO PRODUCTS ENTHALPY**.1 - MID HIGH RNG
      XST=C(121)+X*(C(122)+X*(C(123)+X*C(124)))
      GO TO 1528
C         CURVE FROM PRODUCTS PHI TO PRODUCTS ENTHALPY**.1 - HIGH RANGE
 1526 XST=C(125)+X*(C(126)+X*(C(127)+X*C(128)))
 1528 XAIR=XAIR+(XST-XAIR)*FACT
      FAR=FA*(FZAST-FA)
      XM1=X-1.0
      GASP=(0.999946-(-.00141776*FA+XM1*FAR*(-5.50395775+4.97683907
     1 *XM1)))*XAIR**10
      GO TO 1430
 1530 GASP=XAIR**10
      GO TO 1430
 1560 IF (X.LT.XMIN(1)) GO TO 880
      IF (X.GT.XB2(1)) GO TO 1580
      IF (X.GT.XB1(1)) GO TO 1570
C         CURVE FROM TEMPERATURE TO AIR CP - LOW RANGE
      XAIR=C(129)+X*(C(130)+X*(C(131)+X*C(132)))
      GO TO 1600
C         CURVE FROM TEMPERATURE TO AIR CP - MID LOW RANGE
 1570 XAIR=C(133)+X*(C(134)+X*(C(135)+X*C(136)))
      GO TO 1600
 1580 IF (X.GT.XB3(1)) GO TO 1590
C         CURVE FROM TEMPERATURE TO AIR CP - MID HIGH RANGE
```

```
      XAIR=C(137)+X*(C(138)+X*(C(139)+X*C(140)))
      GO TO 1600
 1590 IF (X.GT.XMAX(1)) GO TO 880
C          CURVE FROM TEMPERATURE TO AIR CP - HIGH RANGE
      XAIR=C(141)+X*(C(142)+X*(C(143)+X*C(144)))
 1600 IF (FA.EQ.0.0) GO TO 1650
      IF (X.GT.XB2(1)) GO TO 1620
      IF (X.GT.XB1(1)) GO TO 1610
C          CURVE FROM TEMPERATURE TO PRODUCTS CP - LOW RANGE
      XST=C(145)+X*(C(146)+X*(C(147)+X*C(148)))
      GO TO 1640
C          CURVE FROM TEMPERATURE TO PRODUCTS CP - MID LOW RANGE
 1610 XST=C(149)+X*(C(150)+X*(C(151)+X*C(152)))
      GO TO 1640
 1620 IF (X.GT.XB3(1)) GO TO 1630
C          CURVE FROM TEMPERATURE TO PRODUCTS CP - MID HIGH RANGE
      XST=C(153)+X*(C(154)+X*(C(155)+X*C(156)))
      GO TO 1640
C          CURVE FROM TEMPERATURE TO PRODUCTS CP - HIGH RANGE
 1630 XST=C(157)+X*(C(158)+X*(C(159)+X*C(160)))
 1640 IF (KMN.EQ.9) GO TO 1370
      CP=XAIR+(XST-XAIR)*FACT
      GO TO 1670
 1650 IF (KMN.EQ.9) GO TO 1390
      CP=XAIR
 1670 XAIR=RAIR+(RST-RAIR)*FACT
      IF (KMN.EQ.8) GO TO 1390
      GASP=1.0/(1.0-XAIR/778.0/CP)
      GO TO 1430
 1700 XH=X**.1
      IF (X.LT.XMIN(2)) GO TO 880
      IF (X.GT.XB2(2)) GO TO 1720
      IF (X.GT.XB1(2)) GO TO 1710
C          CURVE FROM AIR ENTHALPY**.1 TO AIR PHI - LOW RANGE
      XAIR=C(161)+XH*(C(162)+XH*(C(163)+XH*C(164)))
      GO TO 1740
C          CURVE FROM AIR ENTHALPY**.1 TO AIR PHI - MID LOW RANGE
 1710 XAIR=C(165)+XH*(C(166)+XH*(C(167)+XH*C(168)))
      GO TO 1740
 1720 IF (X.GT.XB3(2)) GO TO 1730
C          CURVE FROM AIR ENTHALPY**.1 TO AIR PHI - MID HIGH RANGE
      XAIR=C(169)+XH*(C(170)+XH*(C(171)+XH*C(172)))
      GO TO 1740
 1730 IF (X.GT.XMAX(3)) GO TO 880
C          CURVE FROM AIR ENTHALPY**.1 TO AIR PHI - HIGH RANGE
      XAIR=C(173)+XH*(C(174)+XH*(C(175)+XH*C(176)))
 1740 GASP=XAIR
      IF (FA.EQ.0.0) GO TO 1430
      IF (X.GT.XB2(3)) GO TO 1760
      IF (X.GT.XB1(3)) GO TO 1750
C          CURVE FROM PRODUCTS ENTHALPY**.1 TO PRODUCTS PHI - LOW RANGE
      XST=C(177)+XH*(C(178)+XH*(C(179)+XH*C(180)))
      GO TO 1780
C          CURVE FROM PRODUCTS ENTHALPY**.1 TO PRODUCTS PHI - MID LOW RANG
 1750 XST=C(181)+XH*(C(182)+XH*(C(183)+XH*C(184)))
      GO TO 1780
```

```
 1760 IF (X.GT.XB3(3)) GO TO 1770
C         CURVE FROM PRODUCTS ENTHALPY**.1 TO PRODUCTS PHI - MID HIGH RNG
      XST=C(185)+XH*(C(186)+XH*(C(187)+XH*C(188)))
      GO TO 1780
C         CURVE FROM PRODUCTS ENTHALPY**.1 TO PRODUCTS PHI - HIGH RANGE
 1770 XST=C(189)+XH*(C(190)+XH*(C(191)+XH*C(192)))
 1780 ANS =XAIR+(XST-XAIR)*FACT
      FAR=FA*(FZAST-FA)
      GASP=ANS*(XH*FAR*(-.2046544+.13483566*XH)-.00014444*FA*FA
     1 -2.76576042*FAR*FAR+1.0)
      GO TO 1430
 1950 IF (X.LT.XMIN(1)) GO TO 880
      IF (X.GT.XB2(1)) GO TO 1960
      IF (X.GT.XB1(1)) GO TO 1955
C         COMPUTE H-LAMBDA FROM TEMPERATURE - LOW RANGE
      GASP=C(193)+X*(C(194)+X*(C(195)+X*C(196)))
      GO TO 1430
C         COMPUTE H-LAMBDA FROM TEMPERATURE - MID LOW RANGE
 1955 GASP=C(197)+X*(C(198)+X*(C(199)+X*C(200)))
      GO TO 1430
 1960 IF (X.GT.XB3(1)) GO TO 1965
C         COMPUTE H-LAMBDA FROM TEMPERATURE - MID HIGH RANGE
      GASP=C(201)+X*(C(202)+X*(C(203)+X*C(204)))
      GO TO 1430
 1965 IF (X.GT.XMAX(1)) GO TO 880
C         COMPUTE H-LAMBDA FROM TEMPERATURE - HIGH RANGE
      GASP=C(205)+X*(C(206)+X*(C(207)+X*C(208)))
      GO TO 1430
 1970 IF (X.LT.XMIN(1)) GO TO 880
      IF (X.GT.XB2(1)) GO TO 2010
      IF (X.GT.XB1(1)) GO TO 1990
C         CURVE FROM TEMPERATURE TO FUEL ENTHALPY - LOW RANGE
      GASP=C(209)+X*(C(210)+X*(C(211)+X*C(212)))
      GO TO 1430
C         CURVE FROM TEMPERATURE TO FUEL ENTHALPY - MID LOW RANGE
 1990 GASP=C(213)+X*(C(214)+X*(C(215)+X*C(216)))
      GO TO 1430
 2010 IF (X.GT.XB3(1)) GO TO 2030
C         CURVE FROM TEMPERATURE TO FUEL ENTHALPY - MID HIGH RANGE
      GASP=C(217)+X*(C(218)+X*(C(219)+X*C(220)))
      GO TO 1430
 2030 IF (X.GT.XMAX(1)) GO TO 880
C         CURVE FROM TEMPERATURE TO FUEL ENTHALPY - HIGH RANGE
      GASP=C(221)+X*(C(222)+X*(C(223)+X*C(224)))
      GO TO 1430
      END
```

APPENDIX B

MATRIX COEFFICIENT PREDICTION LOGIC

Definition of Matrix Coefficients

$$\text{Partial Derivative} = C(i,\ j) = \frac{\partial(1.0 - \text{ratio}_i \text{ of terms to be matched})}{\partial\,\text{Variable}_j}$$

Matrix Coefficient	Ratio to be Matched (i)	Independent Variable (j)	Prediction Method
C(1,1)	Turbine flow rate	Compressor beta (BETA1)	Avg. value
C(1,2)	(map demand / supplied)	Turbine Re (P4Q5)	Equation
C(1,3)		Rotor speed (SNL)	Equation
C(1,4)		Turbine temp (T4)	Avg. value
C(2,1)	Shaft horsepower	BETA1	Avg. value
C(2,2)	(Compressor / turbine)	P4Q5	f(PLA)
C(2,3)		XNL	Equation
C(2,4)		T4	Avg. value
C(3,1)	Nozzle flow rate	BETA1	Equation
C(3,2)	(capability / supplied)	P4Q5	Equation
C(3,3)		XNL	Equation
C(3,4)		T4	f(PLA)
C(4,1)	Turbine temp	BETA1	Zero
C(4,2)	limit	P4Q5	Zero
C(4,3)	(T4/Limit)	XNL	Zero
C(4,4)		T4	Avg. value
C(5,1)	Rotor speed limit	BETA1	Zero
C(5,2)	(XNL/Limit)	P4Q5	Zero
C(5,3)		XNL	Avg. value
C(5,4)		T4	Zero
C(6,1)	Compressor corrected	BETA1	Zero
C(6,2)	speed limit	P4Q5	Zero
C(6,3)	(XN1R1/Limit)	XNL	Avg. value
C(6,4)		T4	Zero
C(7,1)	Net thrust limit	BETA1	f(PLA)
C(7,2)	(FN/Limit)	P4Q5	f(PLA)
C(7,3)		XNL	f(PLA)
C(7,4)		T4	f(PLA)
C(8,1)	Compressor discharge	BETA1	Avg. value
C(8,2)	temperature limit	P4Q5	Zero
C(8,3)	(T3/Limit)	XNL	Avg. value
C(8,4)		T4	Zero

```
C       MATRIX COEFFICIENT PREDICTION LOGIC
C
C       A4      = TURBINE AREA SETTING
C       BETA1   = COMPRESSOR OPERATING LINE DEFINITION, BETA
C       PLA     = POWER LEVER ANGLE
C       P1QPR   = ENGINE INLET DELTA (P1/14.696)
C       P2Q1    = COMPRESSOR PRESSURE RATIO
C       P4Q5    = TURBINE EXPANSION RATIO
C       P4Q5M   = TURBINE MAP NON-DIMENSIONAL EXPANSION RATIO
C       P7Q9    = EXHAUST NOZZLE EXPANSION RATIO
C       T1QTR   = ENGINE INLET THETA (T1/518.67)
C       T4      = OPERATING TURBINE INLET TEMPERATURE
C       T4DES   = DESIGN TURBINE INLET TEMPERATURE
C       W1R1    = COMPRESSOR CORRECTED AIRFLOW RATE
C       W4R4    = TURBINE  CORRECTED AIRFLOW RATE
C       W7R7    = NOZZLE CORRECTED FLOW RATE
C       W7RQA8  = NOZZLE FLOW FUNCTION (W7*SQRT(THETA7)/DELTA7/A8)
C       XM      = FLIGHT MACH NUMBER
C       XNL     = COMPRESSOR AND TURBINE ROTATIONAL SPEED
C       XN1R1   = COMPRESSOR MAP CORRECTED SPEED
C       XN4R4   = TURBINE MAP CORRECTED SPEED
C
      DO 247 I1=1,8
      DO 247 I2=1,4
  247 COEF(I1,I2)=0.0
C       EQUATIONS FOR ALL POWER LEVER ANGLES
      COEF(1,1)=CONST1
      COEF(2,1)=CONST2
      COEF(3,1)=FUNCT1(SQRT(T4DES),A4,P2Q1,W7RQA8)
      COEF(8,1)=CONST3
      COEF(3,2)=FUNCT2(XN1R1,XN4R4,W7RQA8,P4Q5**2)
      COEF(2,3)=FUNCT3(T4DES,T4DES*P4Q5,XN1R1**2,XN1R1**3)
      COEF(3,3)=FUNCT4(W7R7**2,W1R1,XN4R4)
      COEF(5,3)=CONST4
      COEF(6,3)=CONST5
      COEF(8,3)=CONST6
      COEF(1,4)=CONST7
      COEF(2,4)=CONST8
      COEF(4,4)=CONST9
      IF (PLA.LT.40.0) GO TO 248
C       EQUATIONS FOR PLA EQUAL TO OR GREATER THAN 40
      COEF(7,1)=CONS10
      COEF(1,2)=FUNCT5(SQRT(P4Q5M),P4Q5M**2,XNL,A4)
      COEF(2,2)=FUNCT6(P4Q5M,P4Q5M**2,T4**2,XNL)
      COEF(7,2)=CONS11
      COEF(1,3)=FUNC07(SQRT(P2Q1),A4,XN1R1,XN1R1**2)
      COEF(7,3)=CONS12
      COEF(3,4)=FUNC08(W7RQA8**2,A4,XNL,XN4R4**2)
      COEF(7,4)=CONS13
      GO TO 249
C       EQUATIONS FOR POWER LEVER ANGLES LESS THAN 40
  248 COEF(7,1)=FUNC09(XM,PLA,W7RQA8,P7Q9)
      COEF(1,2)=FUNC10(XN4R4**2,SQRT(XN4R4),SQRT(BETA1),SQRT(P4Q5M))
      COEF(2,2)=CONS14
      COEF(7,2)=FUNC11(T4DES,PLA,SQRT(BETA1))
      COEF(1,3)=FUNC12(T1QTR,P1QPR,W7R7,SQRT(P2Q1))
      COEF(7,3)=FUNC13(BETA1**2,P7Q9**2,PLA,W4R4)
      COEF(3,4)=CONS15
      COEF(7,4)=FUNC14(XM,PLA,SQRT(T4),T4)
  249 CONTINUE
```

APPENDIX C

TURBINE MAP REGRESSION MODEL

```
C          Z = TURBINE AREA SETTING (INPUT)
C         XN = TURBINE MAP CORRECTED SPEED (INPUT)
C       PSIQ = TURBINE NON-DIMENSIONAL EXPANSION RATIO (INPUT)
C      WTURB = TURBINE MAP FLOW RATIO VALUE (FLOW/DESIGN FLOW) (OUTPUT)
C
      FUNCTION WTURB (Z,XN,RE)
      DIMENSION W(3),X(3)
      ZLABL1=LAYER1 (MINIMUM TURBINE AREA SETTING)
      ZLABL2=LAYER2
      ZLABL3=LAYER3
      ZLABL4=LAYER4 (MAXIMUM TURBINE AREA SETTING)
      X0=XN
      X1=XN/100.0
      X2=RE
      X3=SQRT(X1)
      X4=X1*X1
      X5=X1**1.5
      X6=SQRT(X2)
      X7=X2*X2
      X8=X2**1.5
      X9=X3*X7
      X11=X4/X7
      X14=X3/X6
      X15=X5/X6
      X16=X4/X6
      X18=X4*X6
      X19=X8/X4
      X20=X8/X5
      L=1
      IF (Z.LT.ZLABL2) GO TO 110
      IF (Z.LT.ZLABL3) GO TO 120
      IF (Z.EQ.ZLABL4) GO TO 140
      GO TO 130
  110 RCH=FUNCT1(X0**1.5)
      IF (X2.LT.RCH) GO TO 114
      W(1)=CONST1
      GO TO 115
  114 W(1)=FUNCT2(X3,X9,X11,1./X8,X20,1./X14)
  115 IF (Z.EQ.ZLABL1) GO TO 170
      X(1)=ZLABL1
      L=2
  120 RCH=FUNCT3(X0**0.2)
      IF (X2.LT.RCH) GO TO 124
      W(L)=CONST2
      IF (X0.GT.100.0) W(L)=FUNCT4(X0,X0**4)
      GO TO 125
  124 W(L)=FUNCT5(X5,X9,X11,X14,X16,X18,X20,1./X18,X3/X7)
  125 IF (Z.EQ.ZLABL2) GO TO 170
      X(L)=ZLABL2
      IF (L.EQ.2) GO TO 160
      L=L+1
  130 X03=X0**3
      RCH=FUNCT6((X0-95.)**2,X03,1./X03)
      IF (X2.LT.RCH) GO TO 134
      W(L)=FUNCT7(X0**2,X0**4)
      GO TO 135
  134 W(L)=FUNCT8(X9,1./X9,X11,X19,1./X11,1./X14,X3/X7)
```

```
135 IF (Z.EQ.ZLABL3) GO TO 170
    X(L)=ZLABL3
    IF (L.EQ.2) GO TO 160
    L=L+1
140 RCH=FUNCT9((X0-95.)**2,1./X0**3)
    IF (X2.LT.RCH) GO TO 144
    W(L)=FUNC10(X0**3)
    GO TO 145
144 W(L)=FUNC11(X1,X4,X9,X15,X19,1./X11,1./X14)
145 IF (Z.EQ.ZLABL4) GO TO 170
    X(L)=ZLABL4
160 WTURB=(W(1)*(X(2)-Z)-W(2)*(X(1)-Z))/(X(2)-X(1))
    RETURN
170 WTURB=W(1)
    RETURN
    END
```

```
C           Z = TURBINE AREA SETTING (INPUT)
C          XN = TURBINE MAP CORRECTED SPEED (INPUT)
C        PSIQ = TURBINE PSI/PSI* (INPUT)
C       ETURB = (PSI/EFF)/PSI* (OUTPUT)
C
      FUNCTION ETURB (Z,XN,PSIQ)
      DIMENSION E(3),X(3)
      ZLABL1=LAYER1 (MINIMUM TURBINE AREA SETTING)
      ZLABL2=LAYER2
      ZLABL3=LAYER3
      ZLABL4=LAYER4 (MAXIMUM TURBINE AREA SETTING)
      X1=XN/100.0
      X2=PSIQ
      X3=X1*X2
      X10=X1*X1
      X11=X2*X10
      X12=X10/X2
      X13=X2/X10
      X14=X2*X11
      L=1
      IF (Z.LT.ZLABL2) GO TO 110
      IF (Z.LT.ZLABL3) GO TO 120
      IF (Z.EQ.ZLABL4) GO TO 140
      GO TO 130
  110 E(1)=FUNCT1(X12,X13,X2**1.5,X2**.2,X3**4,X14**3)
      IF (Z.EQ.ZLABL1) GO TO 170
      X(1)=100.0
      L=2
  120 X7=X2*X2/X1
      E(L)=FUNCT2(X2,X10,X11,X2**4,X1**3,X7**3)
      IF (Z.EQ.ZLABL2) GO TO 170
      X(L)=ZLABL2
      IF (L.EQ.2) GO TO 160
      L=L+1
  130 X4=X2/X1
      E(L)=FUNCT3(X1,X2,X10,X4**3,X11**2,X13**4)
      IF (Z.EQ.ZLABL3) GO TO 170
      X(L)=ZLABL3
      IF (L.EQ.2) GO TO 160
      L=L+1
  140 X8=X1/(X2*X2)
      E(L)=FUNCT4(X8,X11,X12,X13,X2**1.5,SQRT(X3))
      IF (Z.EQ.ZLABL4) GO TO 170
      X(L)=ZLABL4
  160 ETURB=(E(1)*(X(2)-Z)-E(2)*(X(1)-Z))/(X(2)-X(1))
      RETURN
  170 ETURB=E(1)
      RETURN
      END
```

APPENDIX D

COMPRESSOR MAP REGRESSION MODEL

```
C        BETA = COMPRESSOR MAP OPERATING LINE REFERENCE (INPUT)
C         PCN = COMPRESSOR MAP CORRECTED SPEED (INPUT)
C         WAC = COMPRESSOR MAP CORRECTED FLOW (OUTPUT)
C          RC = COMPRESSOR MAP PRESSURE RATIO (OUTPUT)
C         ETA = COMPRESSOR MAP EFFICIENCY (OUTPUT)
C
      SUBROUTINE COMP(BETA,PCN,WAC,RC,ETA)
      X1=BETA
      Y1=PCN
      IF (Y1.LT.YMIN) Y1=YMIN       (MINIMUM VALID MAP SPEED)
      IF (Y1.GT.YMAX) Y1=YMAX       (MAXIMUM VALID MAP SPEED)
      YS=SQRT(Y1)
      XS=SQRT(X1)
      Y15=Y1*YS
      X1M=1.-X1
      X1M2=X1M*X1M
      Y1M=100.-Y1
      X1DAMP=1.0
      IF (Y1.GT.100.) GO TO 10
C        CORRECTED FLOW FOR BETA = 1.0 AND SPEED .LE. 100
      WREF=FUNCT1(Y15+Y1M**4,Y1M**5)
C        EFFICIENCY FOR BETA = 1.0 AND SPEED .LE. 100
      EREF=FUNCT2(Y1M**2,YS*Y1M**3,Y15*SQRT(Y1M))
      GO TO 20
C        CORRECTED FLOW FOR BETA = 1.0 AND SPEED .GT. 100
   10 YM1=Y1-100.
      WREF=FUNCT3(YM1**2,YS*YM1,SQRT(YM1)/Y1)
C        EFFICIENCY FOR BETA = 1.0 AND SPEED .GT. 100
      EREF=FUNCT4(Y1,Y1**6)
   20 IF(Y1 .GE. 100.5) GO TO 60
      IF (X1 .GT. 1.0) GO TO 30
C        ADDITIVE DELTA FLOW FOR BETA .LT. 1.0 AND SPEED .LE. 100
      DW=FUNCT5(X1M*X1*Y1M,X1M*Y1M*Y1*X1**2,Y1,Y1M,X1M**2,X1M2*X1M**2,
     1 X1M2*Y1**2*X1M**3,SQRT(X1))
C        ADDITIVE DELTA EFFICIENCY FOR BETA .LT. 1.0 AND SPEED .LE. 100
      DE=FUNCT6(XS,X1M**2,X1M*Y1M*XS,Y1M*X1M**2,X1M*Y1M**2,(X1M*Y1M)**2)
      IF (X1 .GT. 0.99) X1DAMP=(1.0-X1)*100.0
      IF (Y1 .LE. 99.5) GO TO 100
      GO TO 50
   30 DW=0.0
      IF (Y1 .GE. 95.0) GO TO 40
C        ADDITIVE DELTA FLOW FOR BETA .GT. 1.0 AND SPEED .LT. 95
      Y95M=95.-Y1
      XM1=X1-1.0
      DW=FUNCT7(SQRT(XM1*Y95M),XM1*Y95M,XM1*Y95M*X1*XS)
C        ADDITIVE DELTA EFFICIENCY FOR BETA .GT. 1.0 AND SPEED .LE. 100
   40 Y1M2=Y1M*Y1M
      DE=FUNCT8(X1M*Y1M*X1**2,X1M*Y1M*Y1**2,X1M**2,Y1M*Y1*X1M**2,
     1 X1M**2*Y1M**4,X1M**3,Y1*X1M**3*Y1M**3)
      IF (X1 .LT. 1.01) X1DAMP=(X1-1.0)*100.0
      IF (Y1 .LE. 99.5) GO TO 100
   50 DW1=DW
      DE1=DE
      Y1DMP1=100.5-Y1
   60 IF (X1 .GT. 1.0) GO TO 80
C        ADDITIVE DELTA FLOW FOR BETA .LT. 1.0 AND SPEED .GT. 100
   70 DW=FUNCT9(X1M*Y1M,X1M**2,X1M**4)
```


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```
C        ADDITIVE DELTA EFFICIENCY FOR BETA .LT. 1.0 AND SPEED .GT. 100
      DE=FUNC10(X1M*Y1M,YS*X1M**2)
      IF (Y1 .LT. 100.5) GO TO 90
      IF (X1 .GT. 0.99) X1DAMP=(1.0-X1)*100.0
      GO TO 100
C        ADDITIVE DELTA FLOW FOR BETA .GT. 1.0 AND SPEED .GT. 100
   80 DW=0.0
C        ADDITIVE DELTA EFFICIENCY FOR BETA .GT. 1.0 AND SPEED .GT. 100
      DE=FUNC11(X1M*Y1M,YS*X1M**2,X1**2)
      IF (Y1 .LT. 100.5) GO TO 90
      IF (X1 .LT. 1.01) X1DAMP=(X1-1.0)*100.0
      GO TO 100
   90 DW2=DW
      Y1DMP2=1.-Y1DMP1
      DW=DW1*Y1DMP1+DW2*Y1DMP2
      DE=DE1*Y1DMP1+DE2*Y1DMP2
C        FINAL CORRECTED FLOW AND EFFICIENCY
  100 WAC=WREF+DW*X1DAMP
      IF (WAC.GT.CONST1) WAC=CONST1
      IF (Y1.LE.YMIN) WAC=WAC*PCN*CONST2
      ETA=EREF+DE*X1DAMP
      IF (ETA.GT.CONST3) ETA=CONST3
      IF (ETA.LT.CONST4) ETA=CONST4
C        PRESSURE RATIO EQUATION FROM BETA AND CORRECTED FLOW
      RC=CONST5*((WAC/CONST6)**CONST7+1.0-X1)-CONST8
      RETURN
      END
```